Extragalactic Astronomy

THE REALM OF GALAXIES

Those Spiral Nebulae

For a long time galaxies were spotted in the night sky, but were getting classified in catalogues as "***spiral nebulae***". The telescopes were not big enough to resolve the nebulae into a collection of individual stars. The distances to these nebulae were also not accurately known. It was not clear what the nature of these nebulae were, whether they are part of the Milky Way or outside the Milky Way?

In the late 1700s Charles Messier (1730   1817) made a catalogue of several faint extended objects. The Messier catalogue lists 103 diffuse objects. Most of these objects were gaseous nebulae (like the Orion nebula in the Milky Way) and star clusters (like Pleiades). But approximately 40 of them were other galaxies (e.g. M31, M51, M101). Messier (and others of his time) did not realize this.

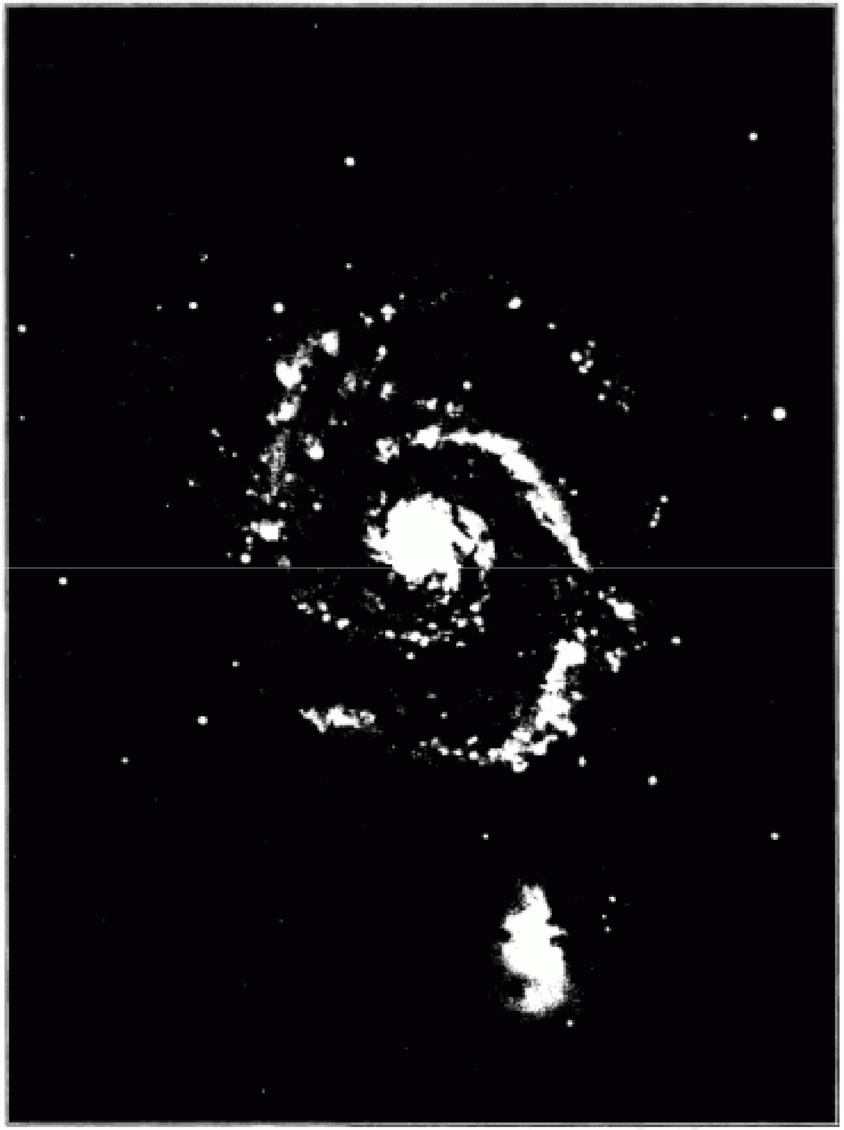
This image of the night sky explains why it is not trivial to spot galaxies

Constellation Cassiopeia and the andromeda galaxy close to it.

Those Spiral Nebulae

A photographic plate from the 1910s

Notice how the galaxy is described as a "***spiral nebula***" in the caption.



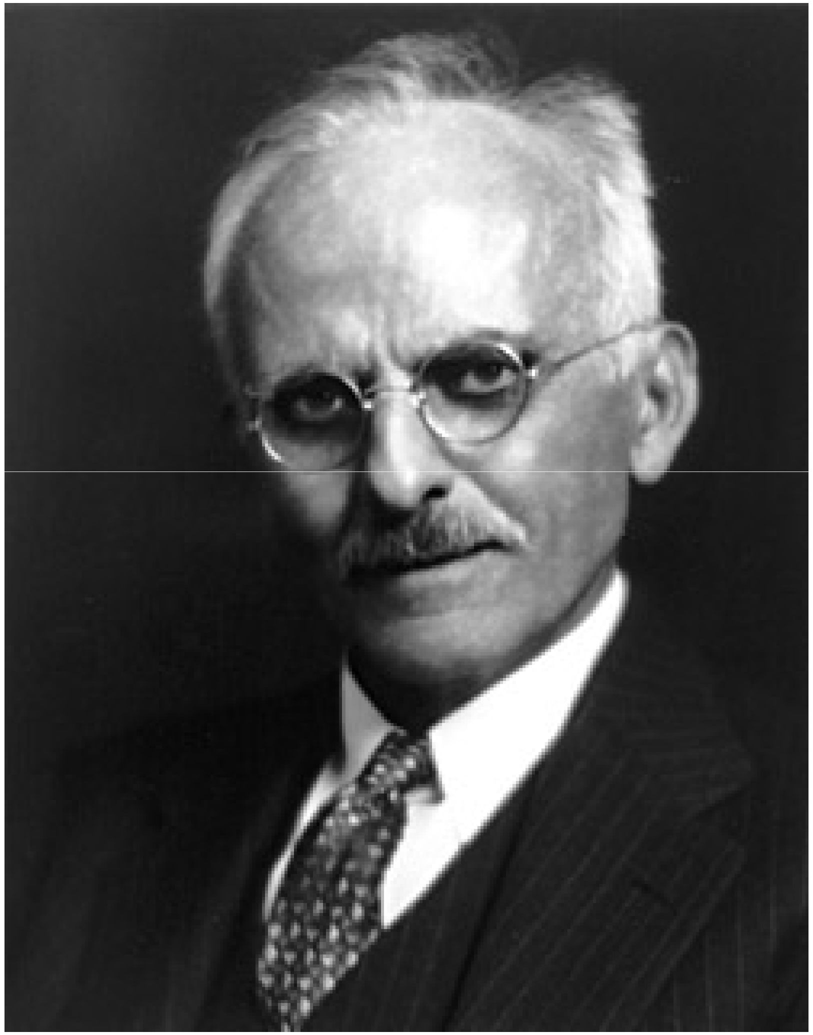
SPIRAL NEBULA *Messier 51 Canum Venaticorum*

Photographed with 60-Inch Reflector on Seed 23 plate, February 7 and 8, 1910
Exposure $3^h\ 55^m$. Enlargement from negative 6.4 diameters. Scale: 1 mm = 4″.2

The Great Debate

On the Nature of Spiral Nebulae

Harlow Shapley



Heber Curtis

The Great Debate

By the early 1900s, there was a raging debate in astronomy regarding the nature of these nebulae. The two sides of the argument had to do with the size of the Milky Way and its relationship to the universe as a whole. Some astronomers argued that the Milky Way was a large part of the entire universe, and that the spiral nebulae were a type of gas clouds inside the Milky Way. The other side argued that these spiral nebulae were island universes like the Milky Way, and they were simply so far away that their stars were not resolved into point sources of light but were instead blurred together to look like a nebula. These disagreements culminated in a public debate in the 1920 between two astronomers representing each side. This event is known in popular science history as the *Great Debate*. The debaters were Harlow Shapley and Hubur Curtis. Shapley is the astronomer who used globular clusters to determine the size of the Milky Way, and this research was also his contribution to the debate. He argued that the spiral nebuale were star systems inside the Milky Way. Heber Curtis's main assertion was that the spiral nebulae are objects like the Milky Way, not objects contained in the Milky Way

contd....

The Great Debate

The data used by both Shapley and Curtis in their debate were not of high enough quality to conclusively solve the debate over the nature of the spiral nebulae. However, both astronomers made points that fundamentally altered our understanding of the Universe, while at the same time drawing other conclusions that have since been proven incorrect. Shapley did show that the Milky Way is larger than it was believed at the time and that the Sun is offset from the center. His incorrect conclusion was that he believed that the Milky Way was so large that it could encompass the spiral nebulae. Curtis' main contribution was to argue that the data available were not of sufficient quality to conclude that the spiral nebulae were inside of the Milky Way.

A detailed write-up on the Shapley – Curtis debate can be found here :

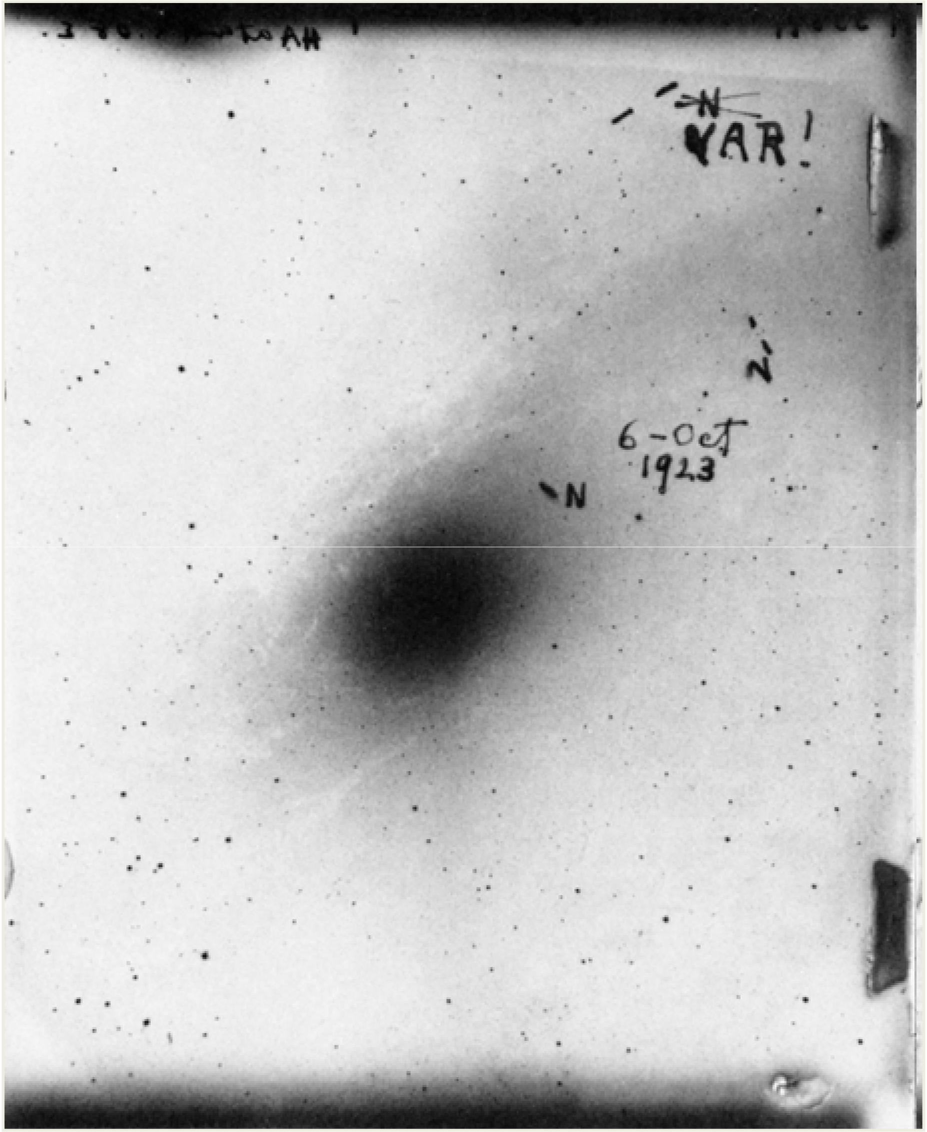
http://apod.nasa.gov/diamond jubilee/debate20.html

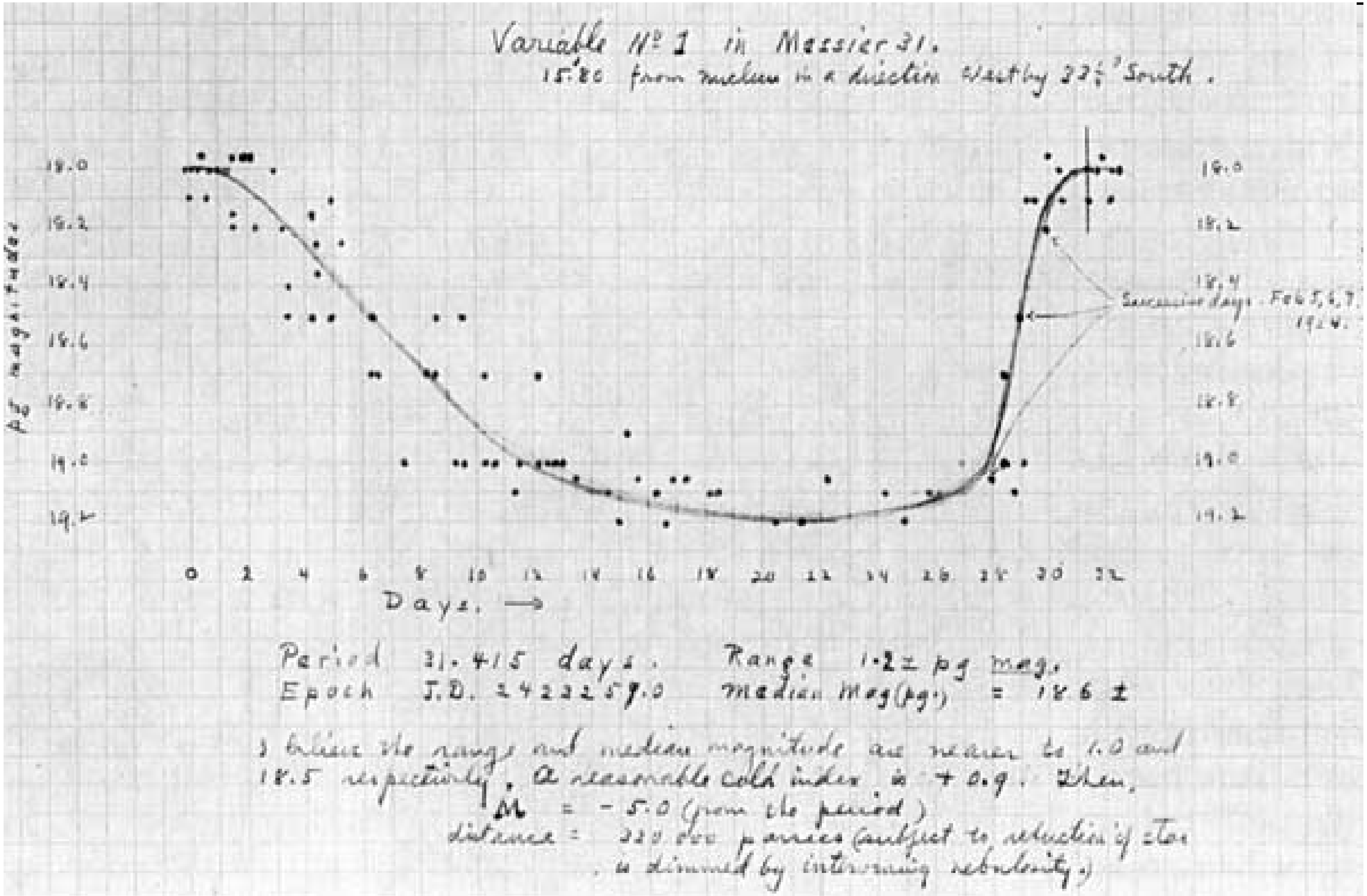
Observations that Settled the Great Debate

Back in the 1920s, with the newly built 100 inch telescope at Mt. Wilson, Edwin Hubble took photographic plate images of some of the nearby spiral nebula. He was able to identifying Cepheid variable stars in them. Using the Cepheid *period – luminosity* empirical relationship (a fresh finding back in the 1920s), Hubble was able to determine distances to some of the spiral nebulae. In the next slide is one of Hubble's original photographic plates of M 31 (Andromeda galaxy).

Hubble's Scribble

The photographic plate of Messier 31 on which Hubble discovered the first Cepheid variable star in a spiral nebula. The objects marked "N" are novae. At first Hubble marked the object in the upper right corner as a nova, but he soon realized it was a variable and marked it "VAR!" – observations with the newly constructed 100 inch telescope on Mt. Wilson.





Here is the letter that has destroyed my universe!

— Harlow Shapley, 1924

The ***previous slide*** shows the light curve of the first Cepheid variable star discovered by Edwin Hubble in the Andromeda Nebula, M31. Using the period of its pulsations, he determined the nebula's distance. Hubble included this graph in his 1924 letter to Harlow Shapley. Hubble found that the distance to M31 comes out something over 300,000 parsecs. This was roughly a million light years, and several times more distant than Shapley's estimate of the outer limits of our own galaxy.

On reading Hubble's letter, Shapley remarked to a colleague who happened to be in his office, "*Here is the letter that has destroyed my universe*." Shapley admitted that the large number of photographic plates that Hubble had obtained were enough to prove that the stars were genuine variables. By August, Hubble had still more variables to report. Before the 1920s ended, astronomers understood that the spiral nebulae lie outside our own galaxy.

Now we know that Shapley was wrong in his theory about the nature of spiral nebula. Hubble's original estimation of the distance to M31 is also off by factors. M31 is at a distance of 770,000 parsec.

CLASSIFICATION BASED ON OBSERVED MORPHOLOGY

Galaxies come in a variety of sizes, shapes and colors, in a wide range of largely inexplicable forms whose relations to one another are not immediately obvious. When faced with great diversity, the first step in studying any class of objects is to classify them into groups based on small numbers of shared characteristics. The hope is that such classification based on observed attributes might reveal any underlying physical relationship that will help us understand those objects.

Galaxy morphology could be indicative of how galaxies formed, their history of interaction with their environment, how they were influenced by internal or external perturbations, the activity centering around the super massive black hole at the center, the galaxy's dark matter, and the galaxy's varied star formation histories.

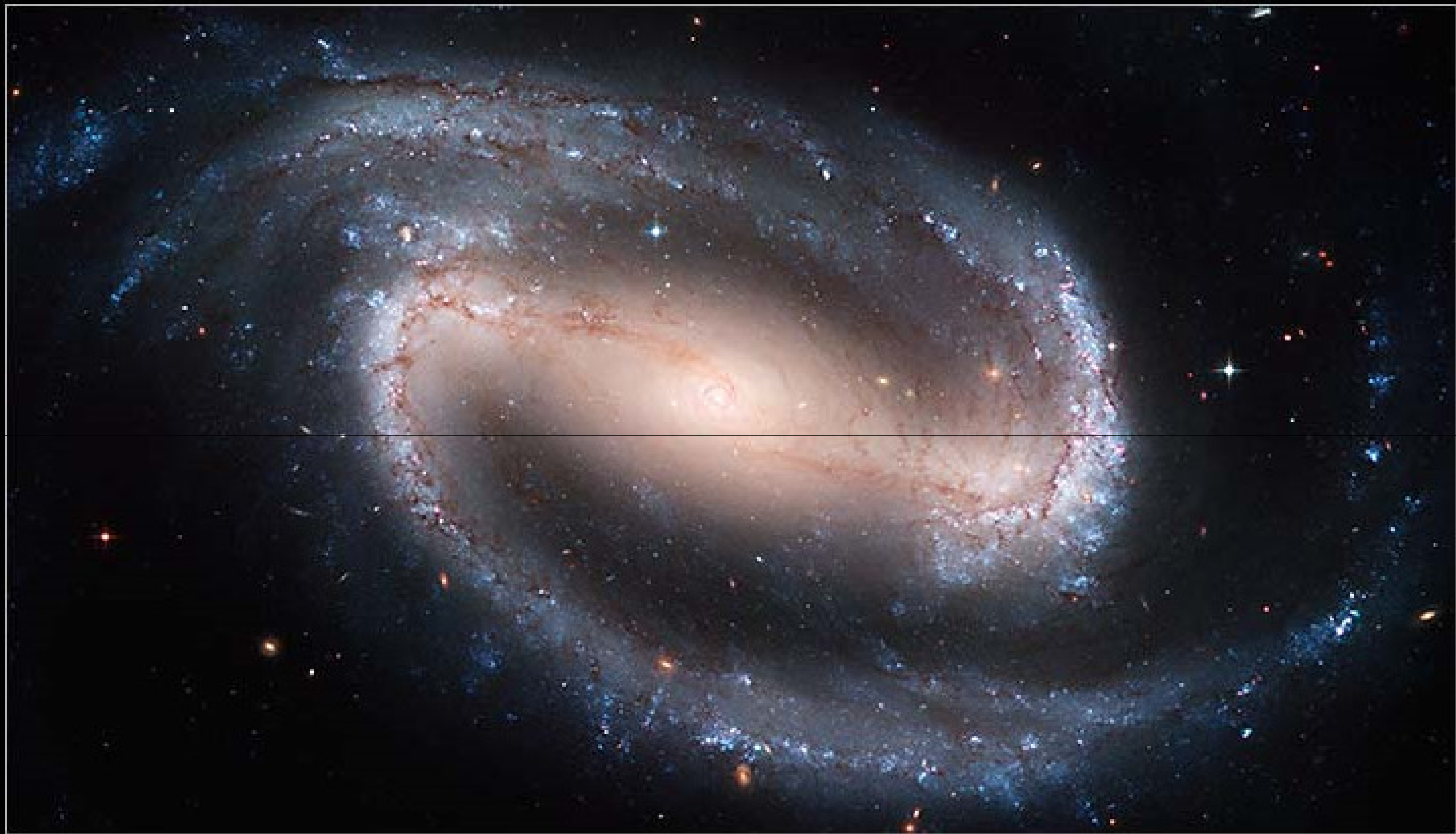
We will look at a formal way to classify galaxies based on their observed morphology

Normal Spiral Galaxy

Normal Spiral Galaxy

Barred Spiral Galaxy

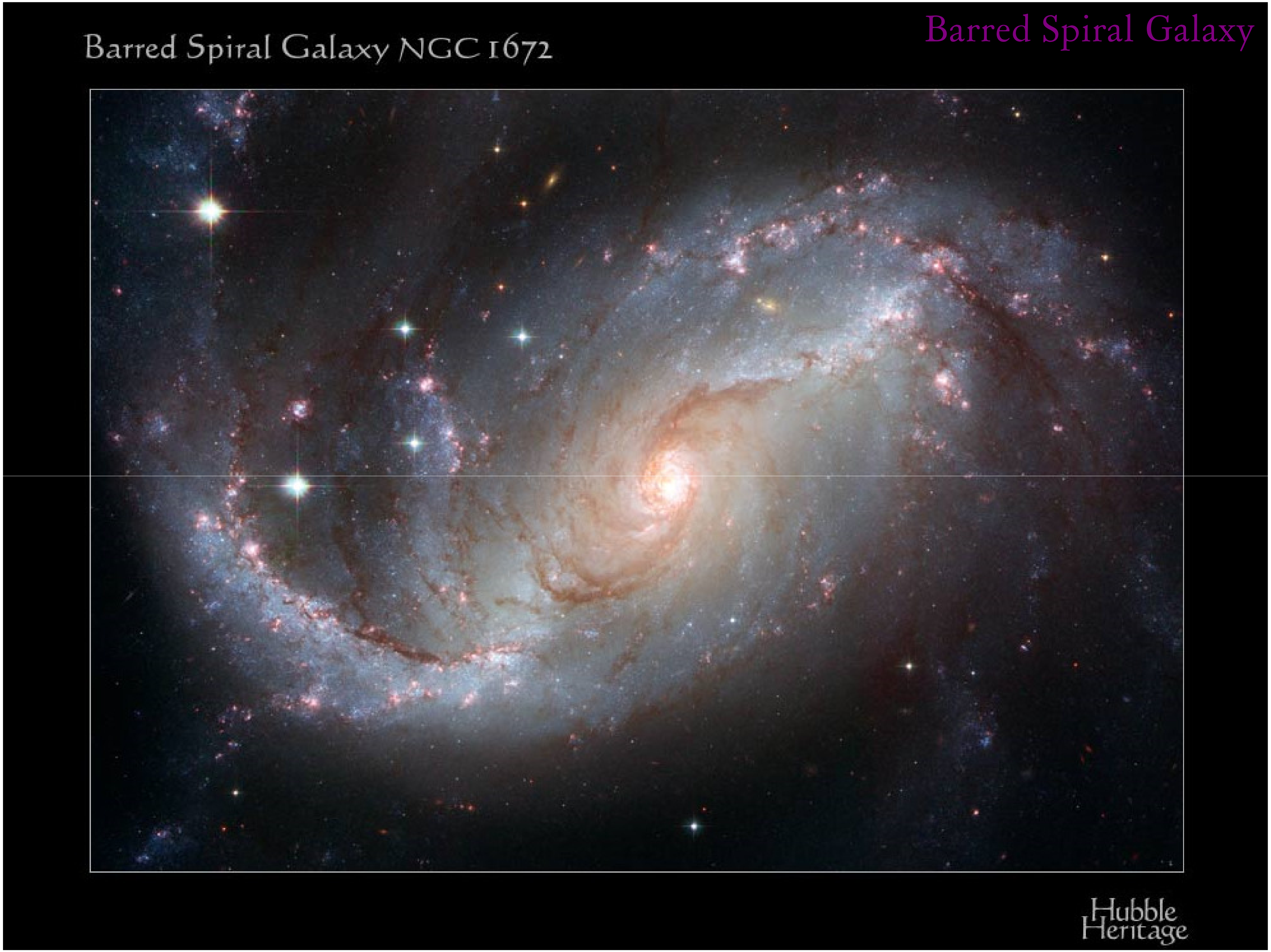
Barred Spiral Galaxy NGC 1300



Hubble Heritage

NASA, ESA and The Hubble Heritage Team (STScI/AURA) • Hubble Space Telescope ACS • STScI-PRC05-01

Barred Spiral Galaxy



Spiral Galaxies

Consists of a disk with spiral arm structure & a central bulge

(a) Normal spirals (S) : have a central bulge and a disk with spiral arms

(b) Barred spirals (SB) : have a central bulge, a disk with spiral arms and a bar structure in the centre linking the bulge to the spiral arms.

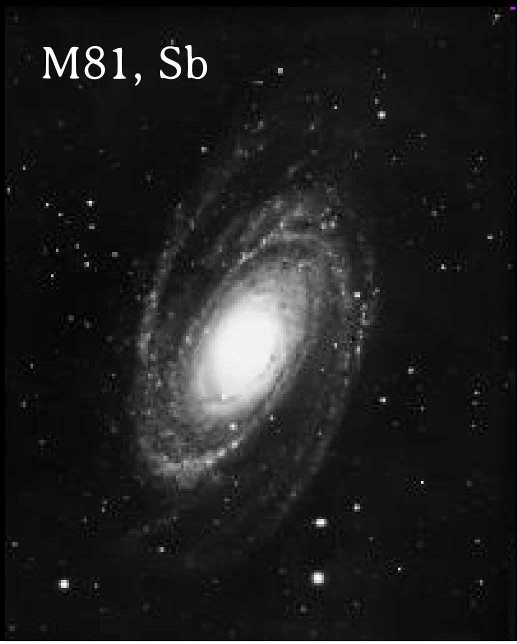
In each of these subclasses, a sequence is defined based on the tightness of spiral arms, the brightness ratio of bulge/disk and the gas content. The sequence is denoted using suffixes: a, ab, b, bc, c, cd, d.

Sa Sb Sc Sd

Bulge is dominant → Bulge is small

Spiral arms are tightly wrapped → Spiral arms are loosely wrapped

Endless Forms of Spirals

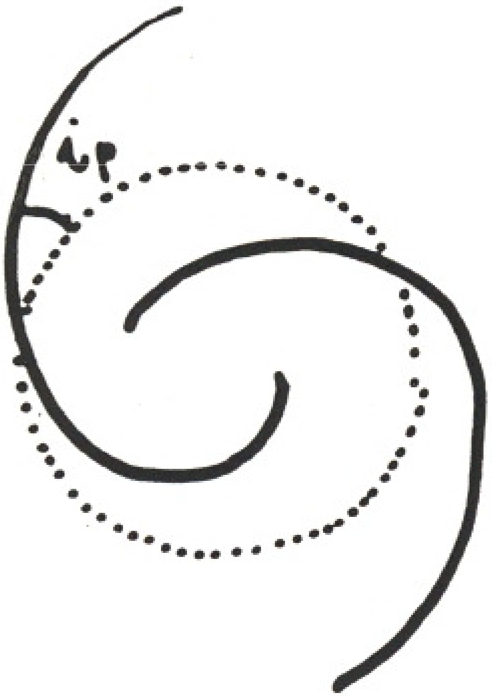


Endless Forms of (Barred) Spirals

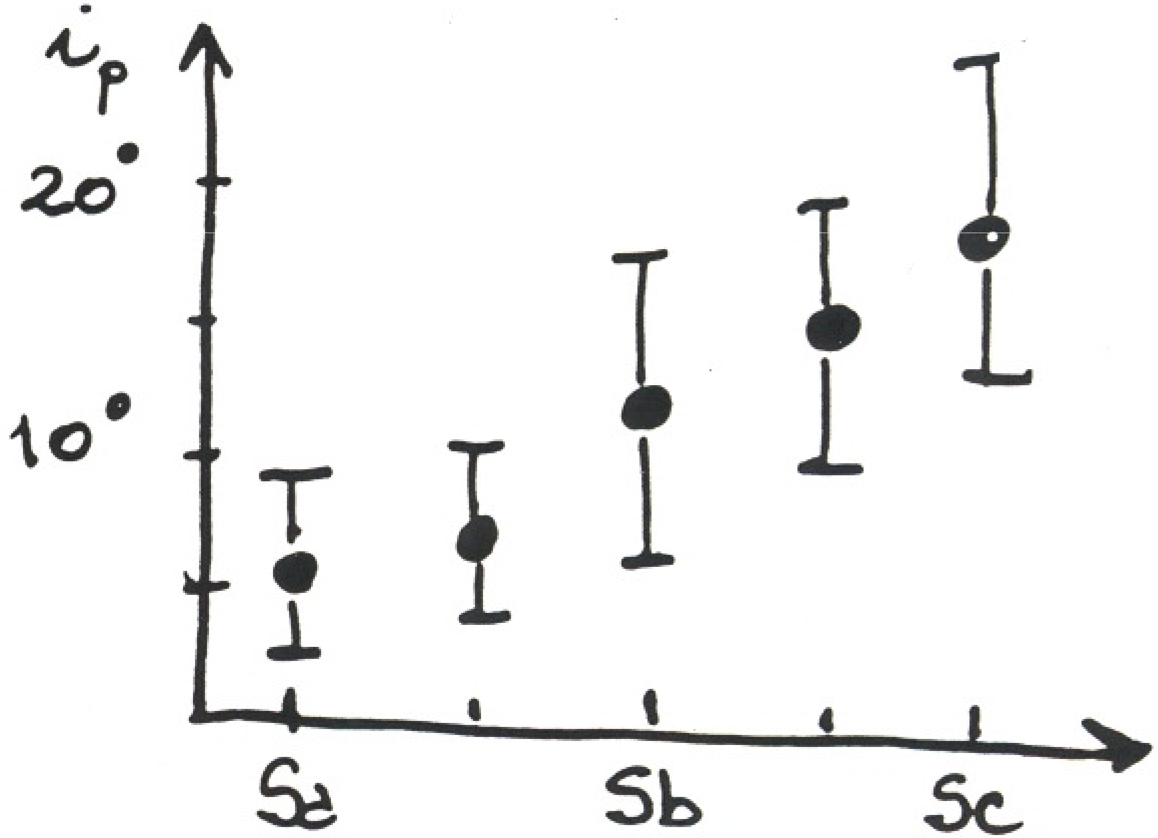
Spiral Galaxies : *some observational trends*

Tightness of the spiral arms is defined in terms of ***pitch angle***

Pitch angle is correlated with Hubble morphology type



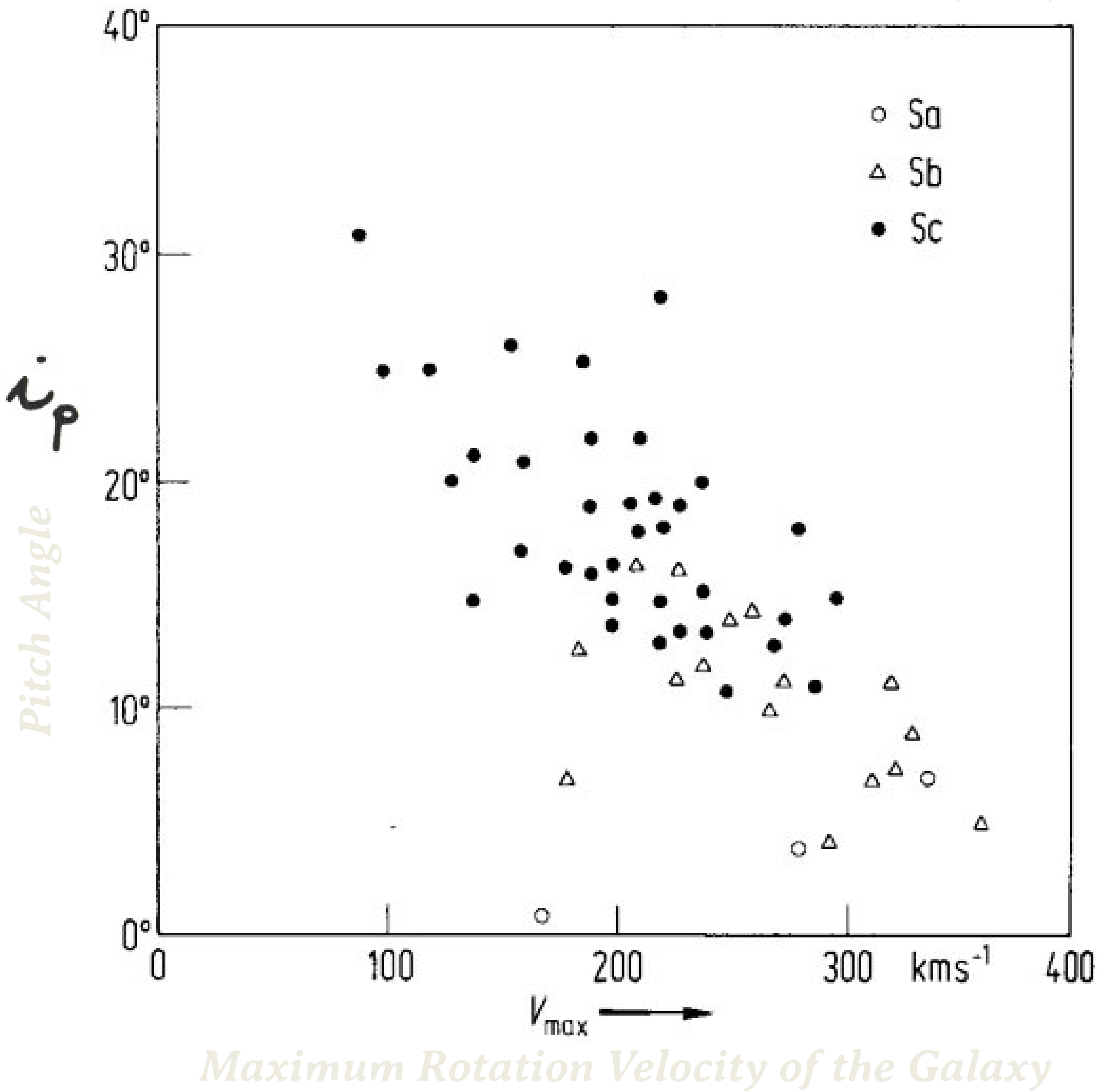
Kennicutt R. C. (1981)



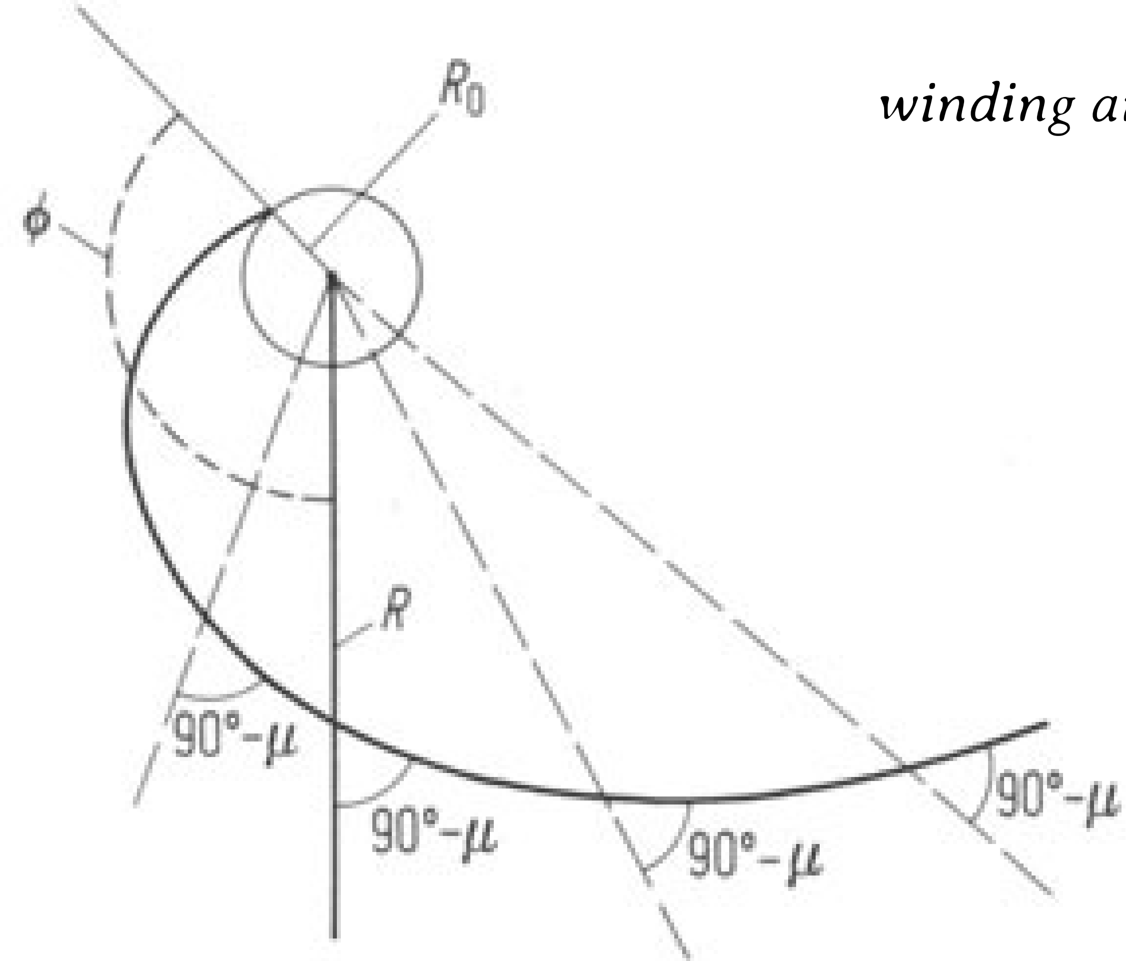
Spiral Galaxies : *some observational trends*

The maximum rotation velocity of spiral galaxies is well correlated with the arm pitch angle, suggesting that the shape of spiral pattern is mainly dictated by kinematic parameters, independent of the physical origin of the arms

Kennicutt R. C. (1981)



Spiral Galaxies

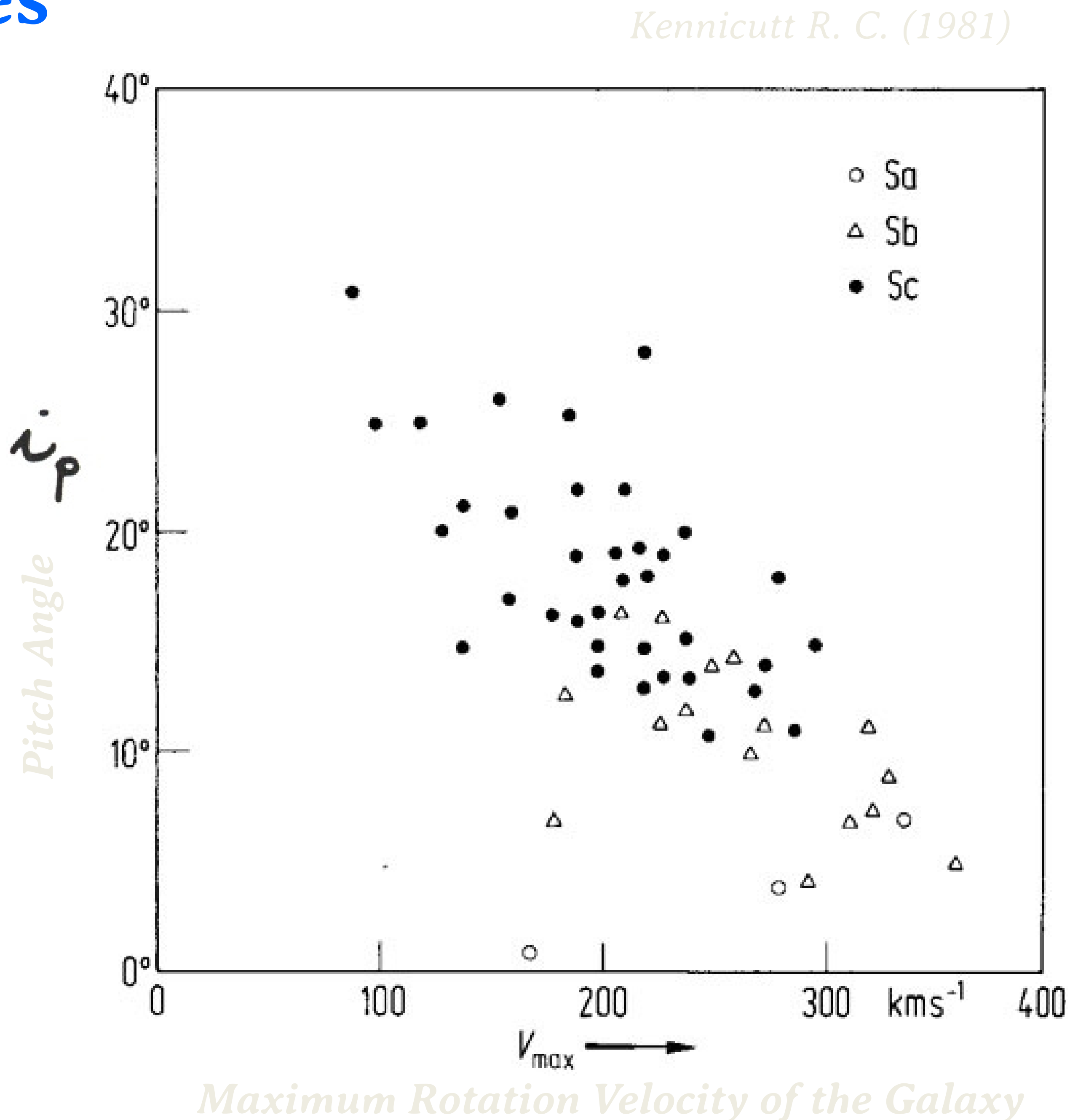


winding angle : Φ

In most spiral galaxies, the pitch angle only slowly changes. Thus one can define the pitch angle for almost any galactocentric radii. The value will be more or less the same.

Spiral Galaxies

The maximum rotation velocity of spiral galaxies is well correlated with the arm pitch angle, suggesting that the shape of spiral pattern is mainly dictated by kinematic parameters, independent of the physical origin of the arms



Spiral Galaxies

Spiral Galaxies : *Getting A Bit Fussy About the Details*

M 51 (Whirlpool Galaxy)

Grand Design Spirals *highly symmetric, smooth, and continuous two-armed spiral pattern*

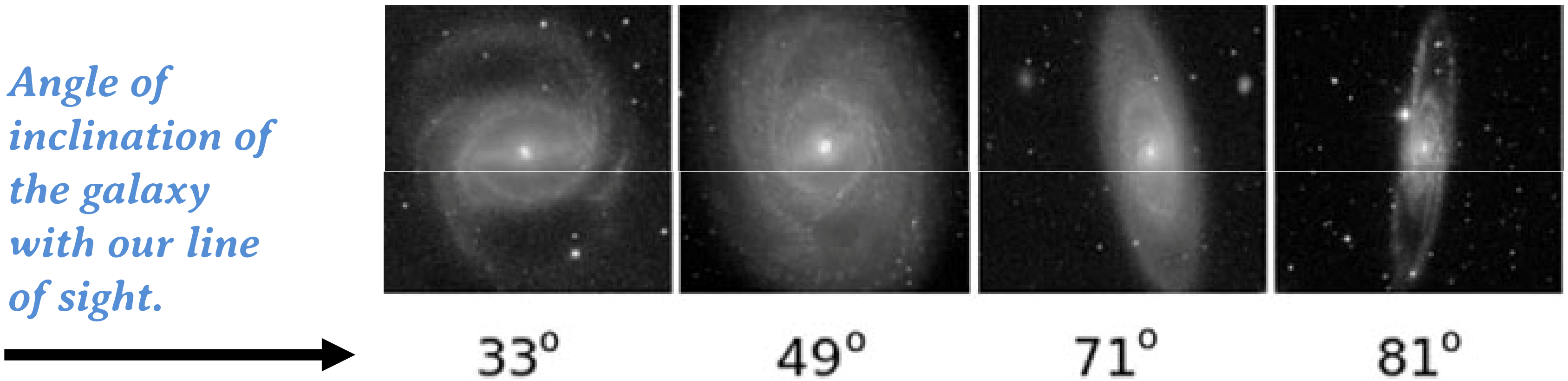
Spiral Galaxies : *Getting A Bit Fussy About the Details*

Flocculent Spirals : ***disjoint, fragmented, patchy spiral arms that are hard to trace***

Galaxy Morphology Classification is Non-Trivial

Classification of galaxies based on their perceived morphology might seem like a trivial task. But there are several factors that can bias our judgment. For example, here are image of four galaxies of likely similar morphology but viewed at different inclinations. The galaxies are (left to right) NGC 1433, NGC 3351, NGC 4274, and NGC 5792.

Angle of inclination of the galaxy with our line of sight.

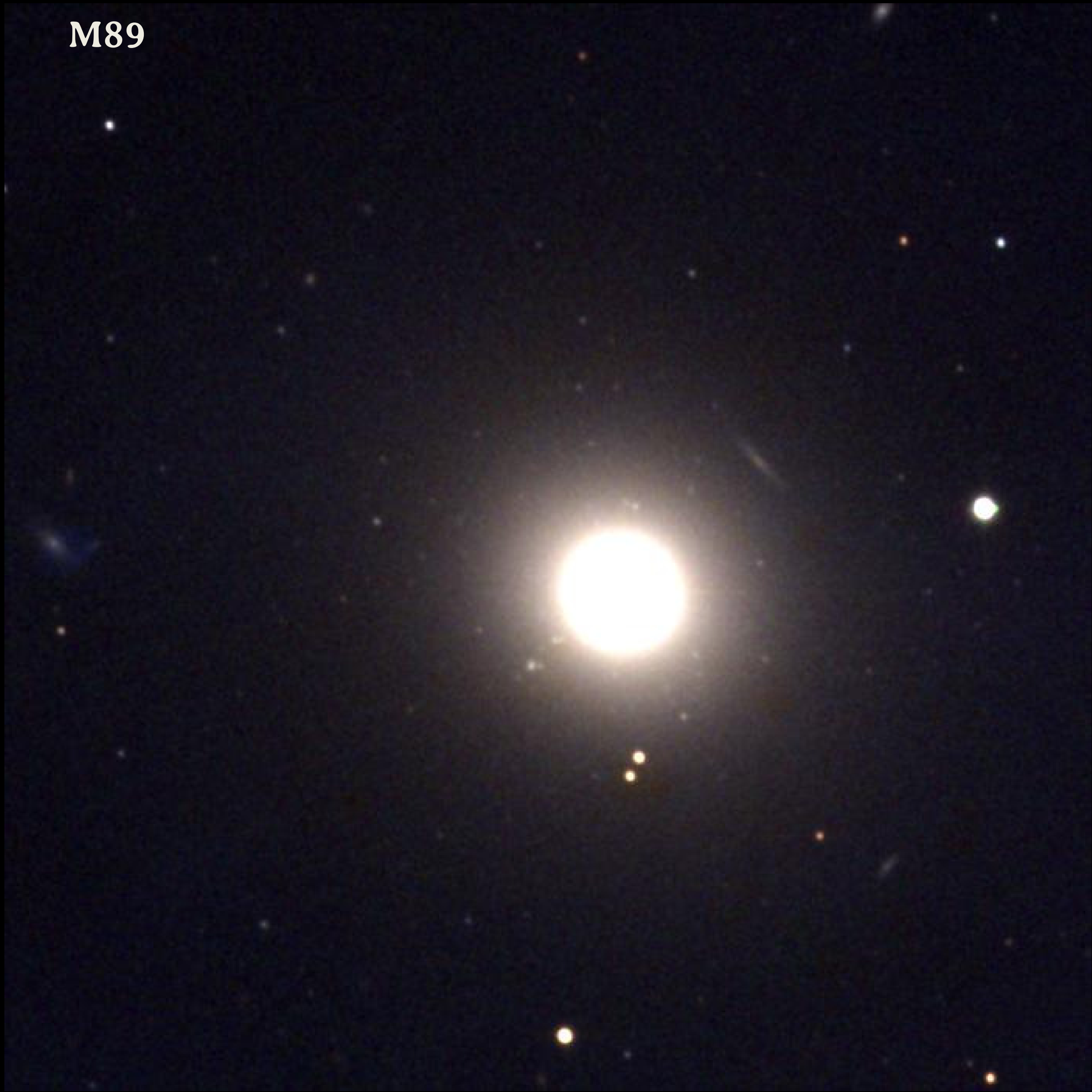


Random orientations of these galaxies makes it difficult to perceive all structural details, thereby biasing the morphological identification. *Orientation of the galaxy is thus one crucial factor affecting morphological classification*. The other is distance to the galaxy. It is easier to see morphological details for nearby galaxies. The angular size of very distant galaxies will be small making it difficult to see detailed morphological features (like bars, spiral pattern, bulges etc).

Elliptical Galaxies

Elliptical Galaxies

Elliptical Galaxies



Elliptical Galaxies

Featureless galaxies that appear to be just a ball of stars.

Do not have obvious dust lanes and gas clouds like what we see in spiral galaxies.

Low H I gas content

Very low H_2 gas content

Little star formation.

Overall colors and spectra of elliptical galaxies dominated by old stellar population.

Elliptical galaxies are subdivided based on their <u>*perceived*</u> ellipticity

$$e = 1 - b/a,$$

a : semimajor axis, ***b*** : seminminor axis

ratio ***b/a*** is often referred to as the *axis ratio*.

Note: The above expression is the *flattening factor* of the ellipse and not the true *eccentricity*. The *ellipticity* of an ellipse can be expressed in terms of either its *flattening factor* or its *eccentricity*.

Elliptical galaxies are found over a broad range in ellipticity,

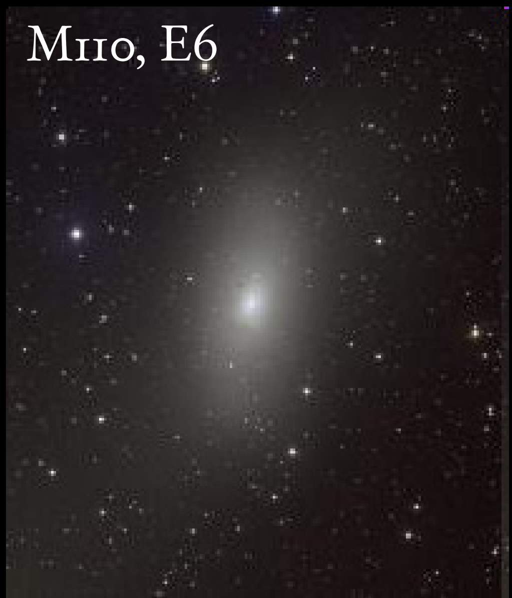
$$0 \leq e \leq 0.7$$

Referred to using the short form notation,

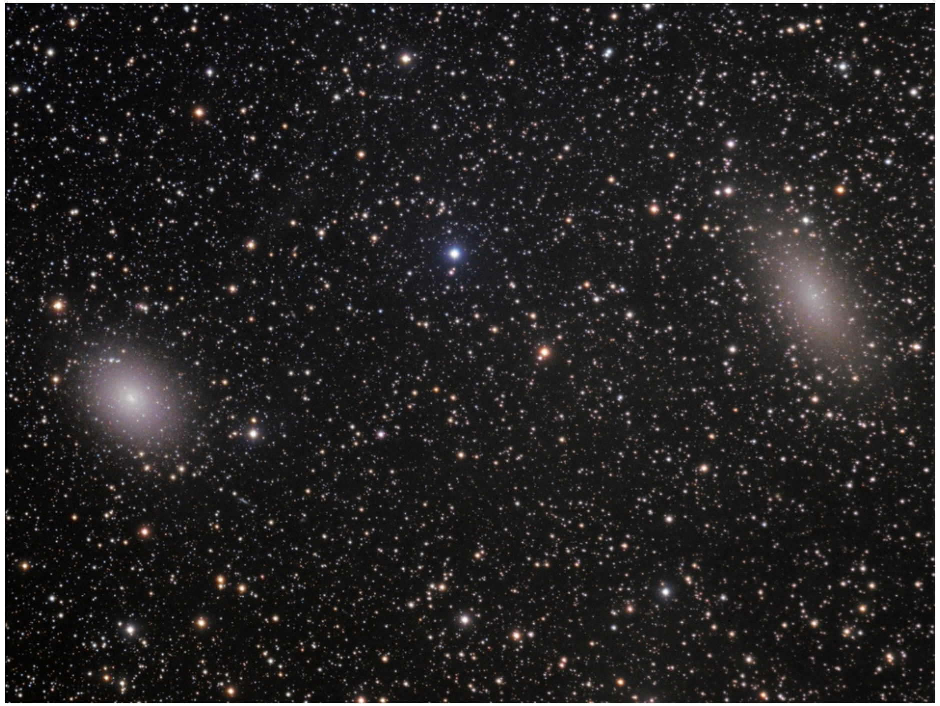
En, where n = 10e.

Example: an elliptical galaxy with axis ratio b/a = 0.4 will be written as E4. E0 galaxies are nearly circular in shape. E7 will be the most flattened ellipticals.

Endless Forms of Ellipticals



Endless Forms of Ellipticals

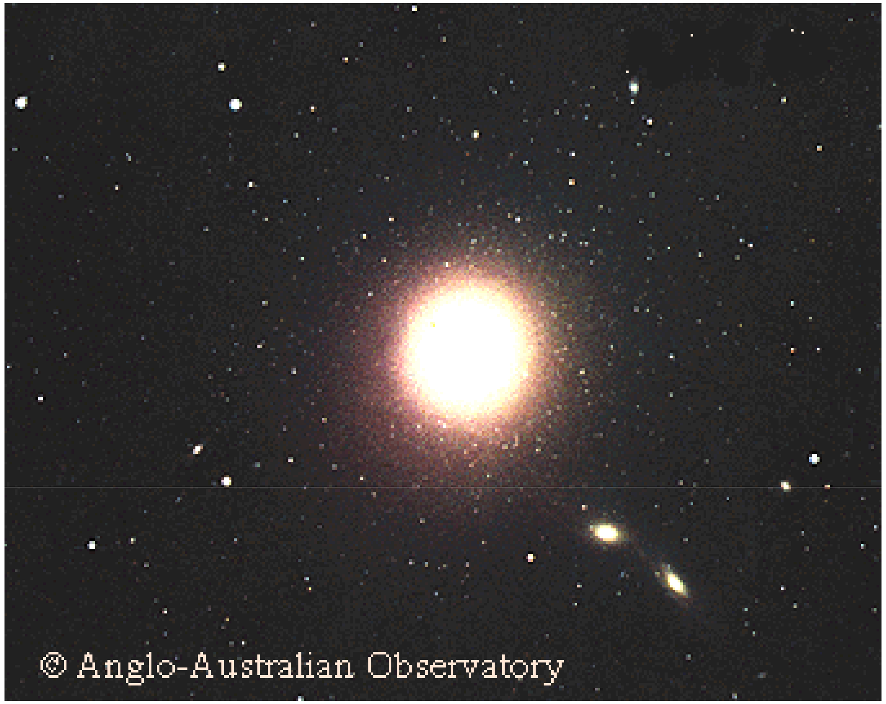


Smallest galaxies are ellipticals (dwarf ellipticals, dwarf Spheroidals)

$M_B \sim -10$

$M_{visible} \sim 10^8 M_\odot$

D (size) ~ 0.3 kpc



Most luminous and massive galaxies are also ellipticals (cD galaxies)

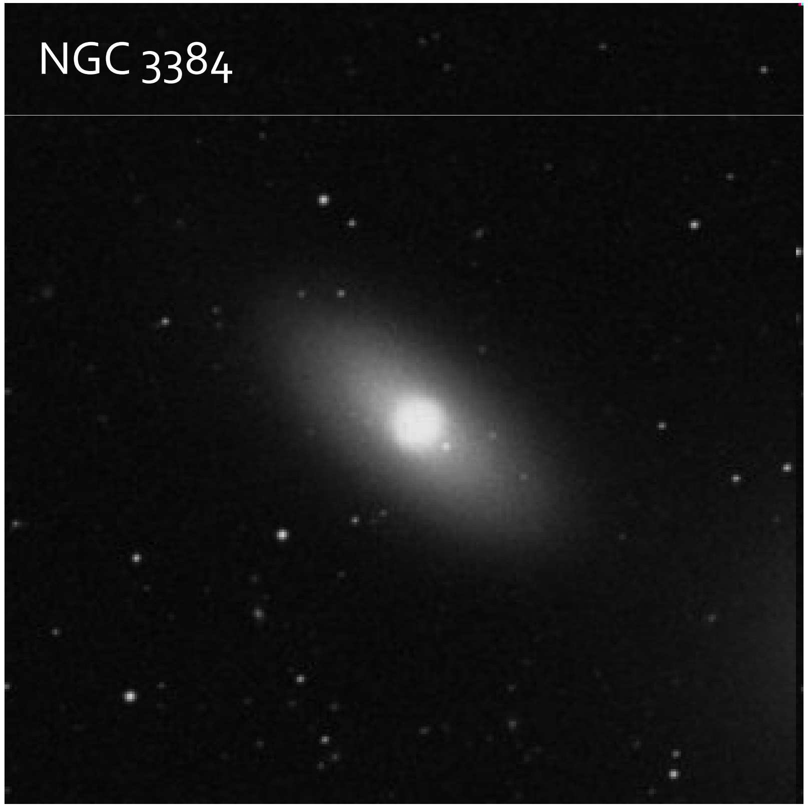
$M_B \sim -23$

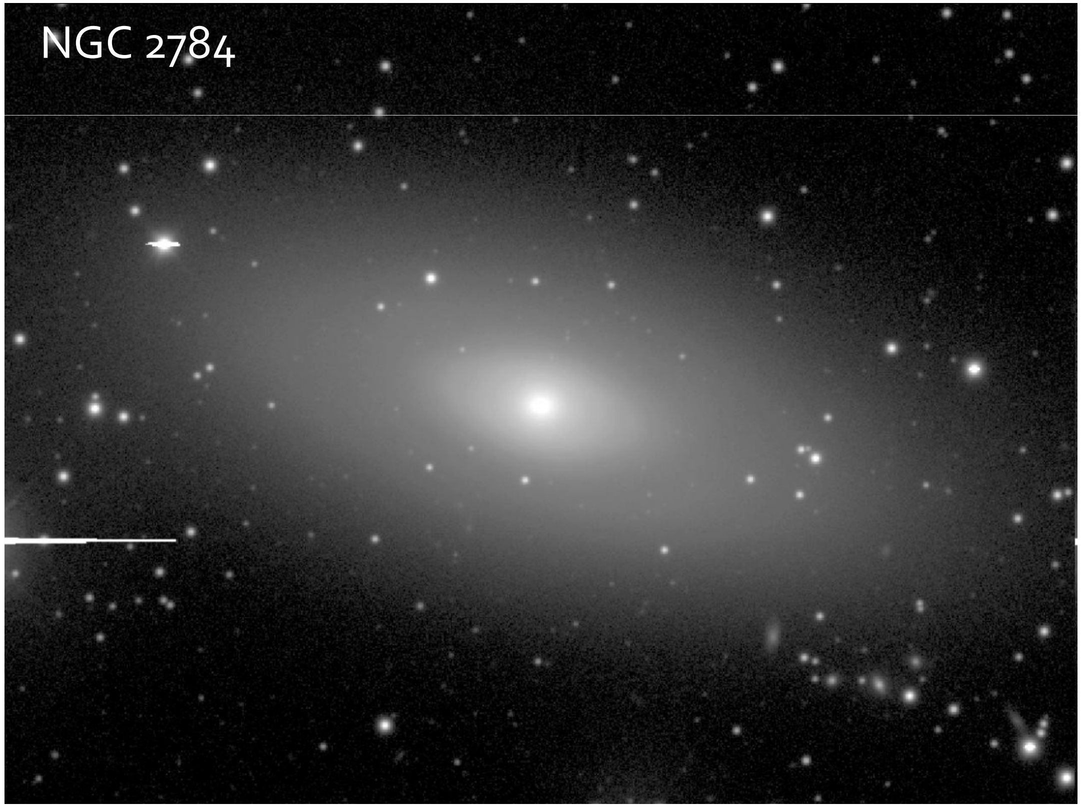
$M_{visible} \sim 10^{12} M_\odot$

D (size) ~ 700 kpc

Lenticular Galaxies (S0 galaxies)

Lenticular or S0 galaxies do not have a distinct spiral structure. Instead they contain a central bulge and a large enveloping region of relatively unstructured brightness which appears like a disk without spiral arms.





Irregular Galaxies

These are galaxies with weak or no regular structure.

Two subclasses within this group : Irr I & Irr II

Irr I galaxies show some spiral structure, but it appears to have been disrupted (e.g. LMC and SMC).

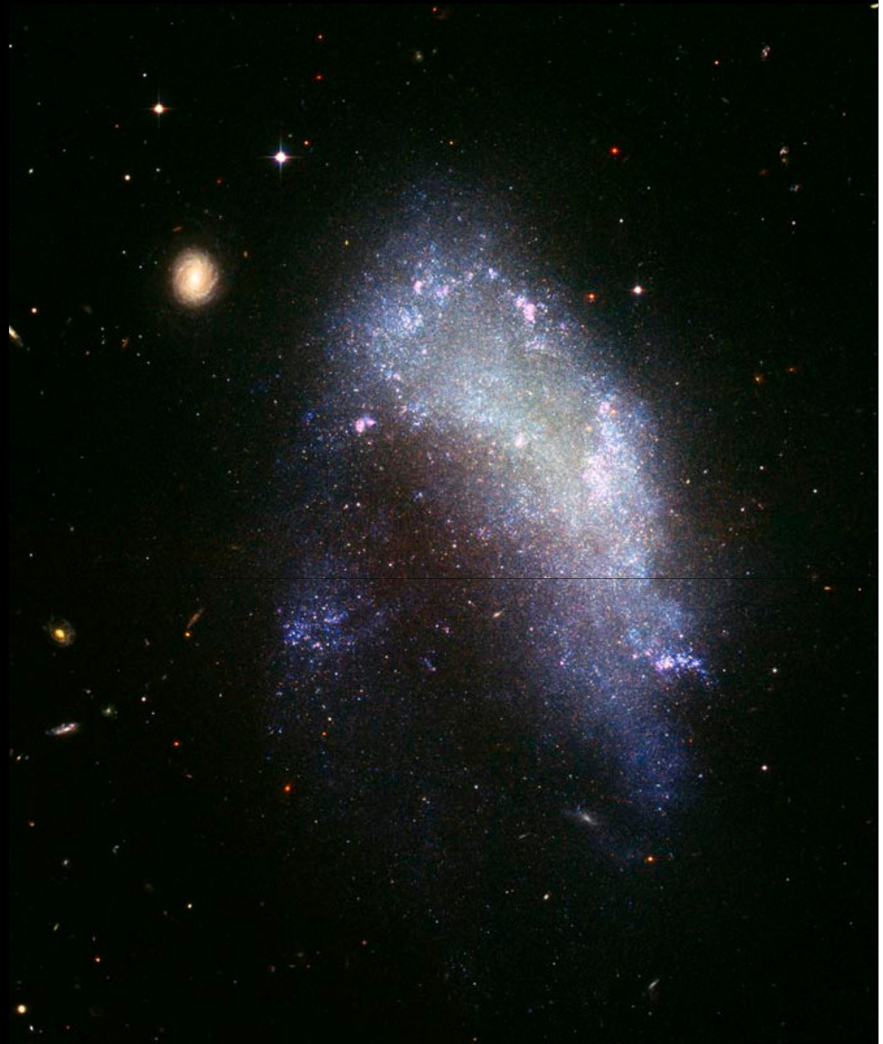
Irr II galaxies are much more disturbed than Irr I galaxies and look like they have been victims of some type of violent event which has completely disrupted their original shape.

Irr galaxies are dominated by young stellar population.

Most Irr galaxies exhibit significant star formation.

From the southern hemisphere, we see the Magellanic clouds which are irregular galaxies and satellites of the Milky Way. In this image is the Small Magellanic Cloud next to a globular cluster in the southern Galactic halo. Distance to SMC is about 60 kpc.

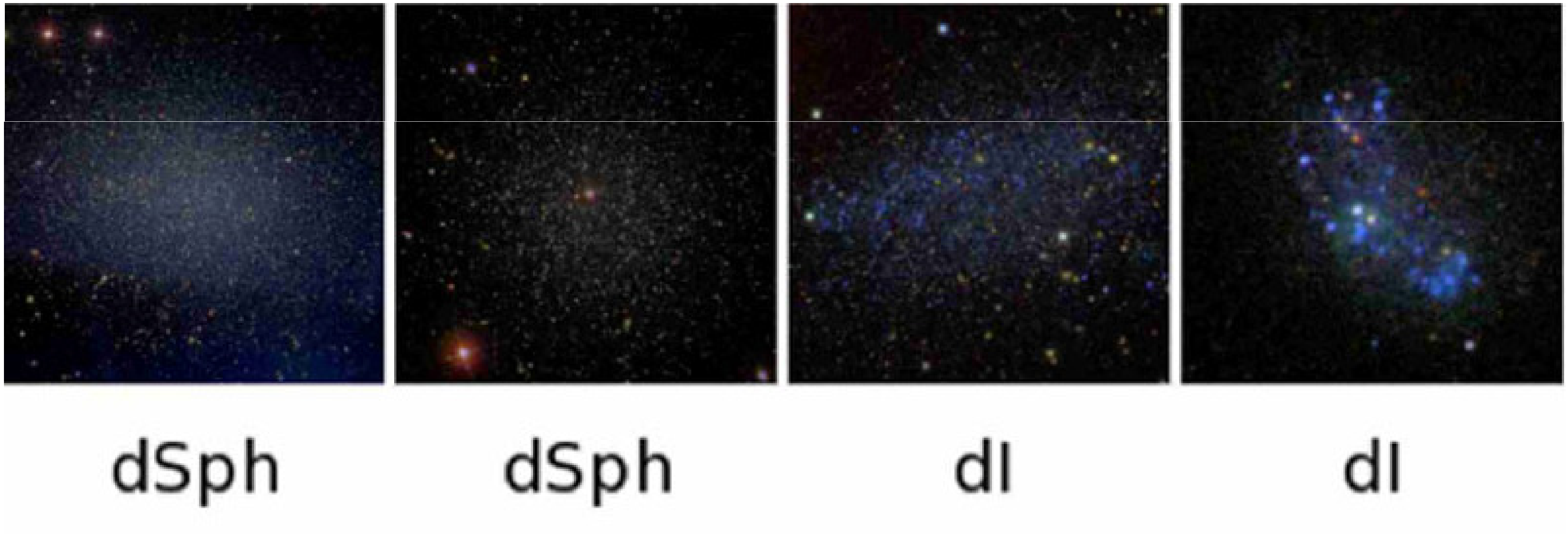
LMC - Irr I galaxy - SBm



NGC 1427A - Irr II galaxy

Irregular Galaxies & other Dwarfs

- Most irregular galaxies are dwarfs (low mass, small size) and are found as satellites of spiral or giant ellipticals.
- Not all dwarf galaxies are irregulars. There are elliptical dwarfs also called *dwarf spheroidal* (dSph) galaxies, and dwarf spirals also.



Four dwarf galaxies in the Local Group (the galaxy group to which Milky Way belongs). From left to right: Leo I, Leo II, Leo A, and DDO 155 (all SDSS color images)

A rough summary of properties of galaxies of various morphology

Table 18.1 General Properties of Galaxies

Property	Disks (Spirals)	Irregulars	Dwarf Ellipticals	Giant Ellipticals
Diameter (ly)	90×10^3	20×10^3	30×10^3	150×10^3
Mass (sun = 1)	10^{11}	10^6	10^5 to 10^7?	10^{13}
Luminosity (Sun = 1)	10^{10}	10^9	10^8	10^{11}
Color	Bluish (disk), reddish (halo and nucleus)	Bluish	Reddish	Reddish
Neutral gas (fraction of mass)	5%	15%	Less than 1%	Less than 1%
Types of star	Young (disk), old (halo and nucleus)	Young	Old	Old

Note: Mass and luminosity are given in solar masses and solar luminosities, respectively.

Classification of galaxies based on observed morphology is an interesting and tricky exercise. Images of millions of galaxies are available now, and to deal with the morphological classification of such a large database, a team of astronomers have come up with an online citizen's science project called Galaxy Zoo, where anyone interested is given the opportunity to work with images of galaxies obtained through some of the most ambitious surveys in the history of astronomy, including the Sloan Digital Sky Survey (SDSS) and one of the largest HST Treasury Programs CANDLES (Cosmic Assembly Near-IR Deep Extragalactic Legacy Survey)

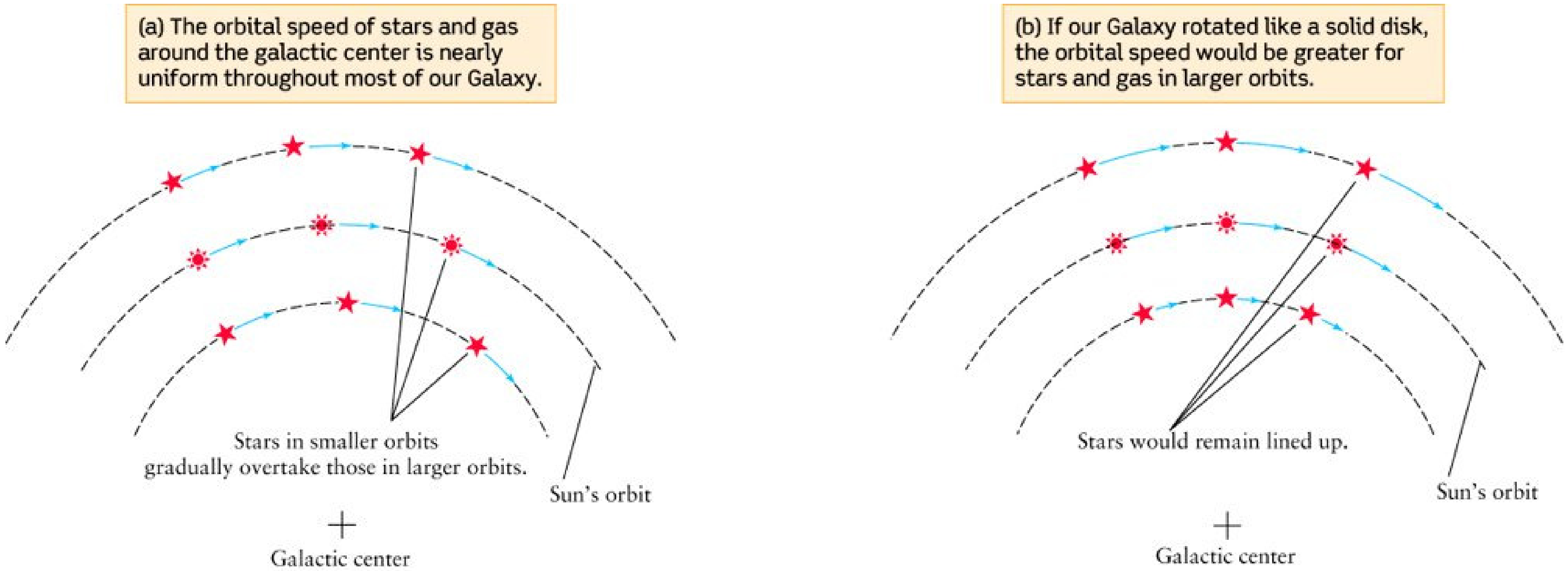
http://www.galaxyzoo.org/

Spiral Structure & The Winding Problem

- The origin of the spiral structure in galaxies has been a mystery. What triggers the formation of spiral structure? What sustains it? Why are some spirals barred? These are questions for which there are yet to be some definitive answers.

- Some clues to the nature of the spiral arms can be gathered by studying the circular motion of the stars and gas that form the spiral arms.

  The rotation of stars and gas in spiral galaxies exhibit what is known as *differential rotation*. Unlike rigid rotators, the disk of spiral galaxies rotate with almost constant linear circular velocity (and not angular velocity) as a function of radius from the galactic center. *The difference is shown pictorially in figure next.*



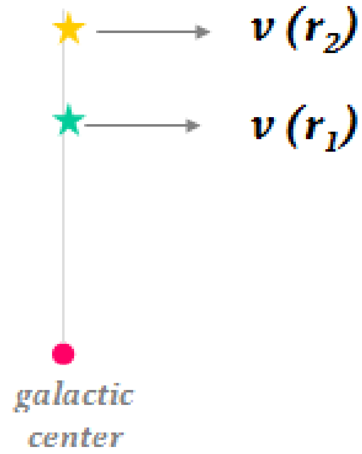
In spiral galaxies, linear velocity is nearly constant such that

$$\Omega(r) = \frac{V(r)}{r} \sim \frac{const}{r}$$

thus **Ω** decreases as ***r*** increases

Spiral Structure & The Winding Problem

- Consider two stars along the same line of sight moving in circular orbits in the disk at r_1, r_2 moving with circular velocities that are comparable $\mathbf{V(r_1) \sim V(r_2)}$ such that the orbital periods $\mathbf{P_2 > P_1}$



$$\Omega_1 P_1 = 2\pi = \Omega_2 P_2$$

The time in which star 1, will gain half an orbit on star 2

$$t_{1/2}(\Omega_1 - \Omega_2) = \pi$$

$$t_{1/2} = \frac{\pi}{\Omega_1 - \Omega_2} = \frac{\pi}{(2\pi/P_1) - (2\pi/P_2)} = \frac{1}{2}\,\frac{P_1 P_2}{P_2 - P_1}$$

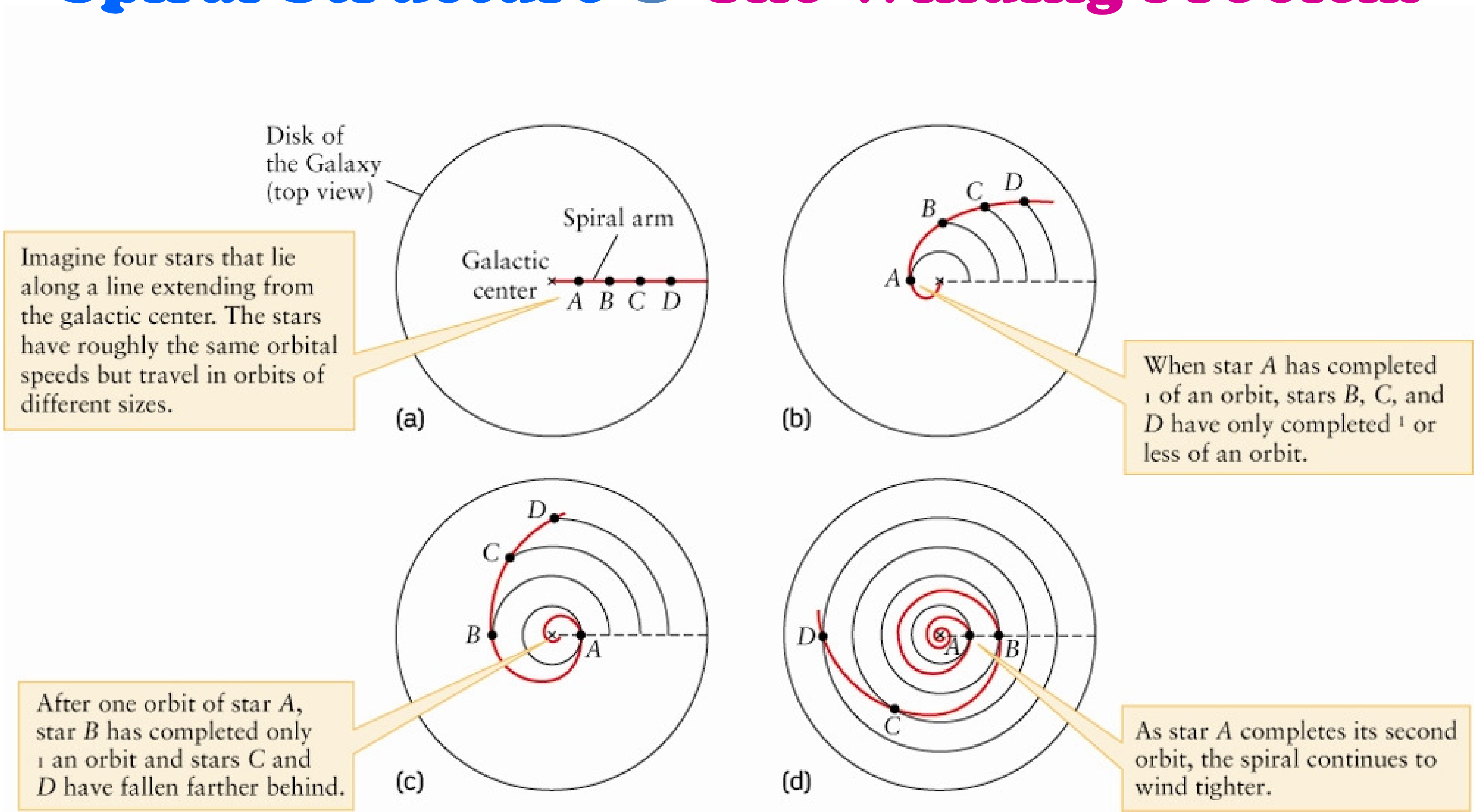
From observations of rotation velocities of stars and gas within the Milky Way we can take any two values such as

$\mathbf{r_1 = 6\ kpc,\ V(r_1) \sim 220\ km/s}$ **&** $\mathbf{r_2 = 10\ kpc,\ V(r_2) \sim 220\ km/s}$

yields, $\mathbf{P_1 \sim 1.12 \times 10^8}$ **yrs and** $\mathbf{P_2 \sim 2.78 \times 10^8}$ **yrs**

$\mathbf{t_{1/2} \sim 9 \times 10^7}$ **yrs,** which means it does not take very long for two stars along the same line of sight to be on opposite sides of each other in the galaxy.

Spiral Structure & The Winding Problem



Spiral Structure & The Winding Problem

Since galactic disks rotate differentially over most of their radii (as evidenced by the characteristic flat rotation curves observed spectroscopically), a line of objects along the same radial direction (arm) will quickly become curved as the galaxy rotates. Since the inner regions revolve faster than those at the edges, the arm will quickly become wrapped around the galaxy in an increasingly tight spiral. This is known as the ***winding problem***, and led to the realization that stars cannot be permanently locked to spiral arms. If it were so, then a given spiral structure will be obliterated within a few rotations (the pattern will become too tight).

The inference is therefore that spiral arms of spiral galaxies have to be transient structures (structures that emerge and fizzle out over time). The popular hypothesis on the origin of spiral arms invokes the idea of some kind of a *self propagative density wave* in the disk of the galaxy. The density waves compresses ISM materail as it slowly sweeps through the disk, thereby triggering star formation through gravitational instability. The lifetimes of the most massive, luminous stars is short enough that they are only found along the spiral arms, not in between them. At present the density wave idea remains a hypothesis lacking sufficient observational backing

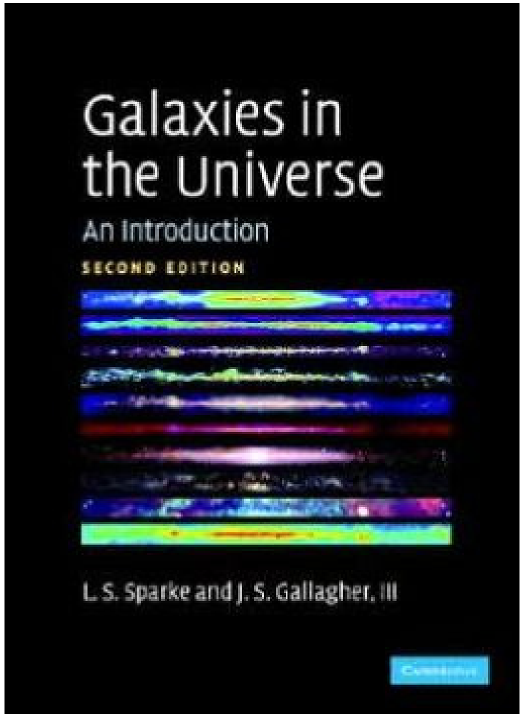
To read a technical article on the density wave theory see

On the Spiral Structure of Disk Galaxies

Lin, C. C.; Shu, Frank H., Astrophysical Journal, Vol 140, 1964.

http://adsabs.harvard.edu/doi/10.1086/147955

Also read Sec 5.2.2 "Theories for Spiral Structure" of *Galaxies in the Universe (Second Edition)* book by Sparke & Gallagher



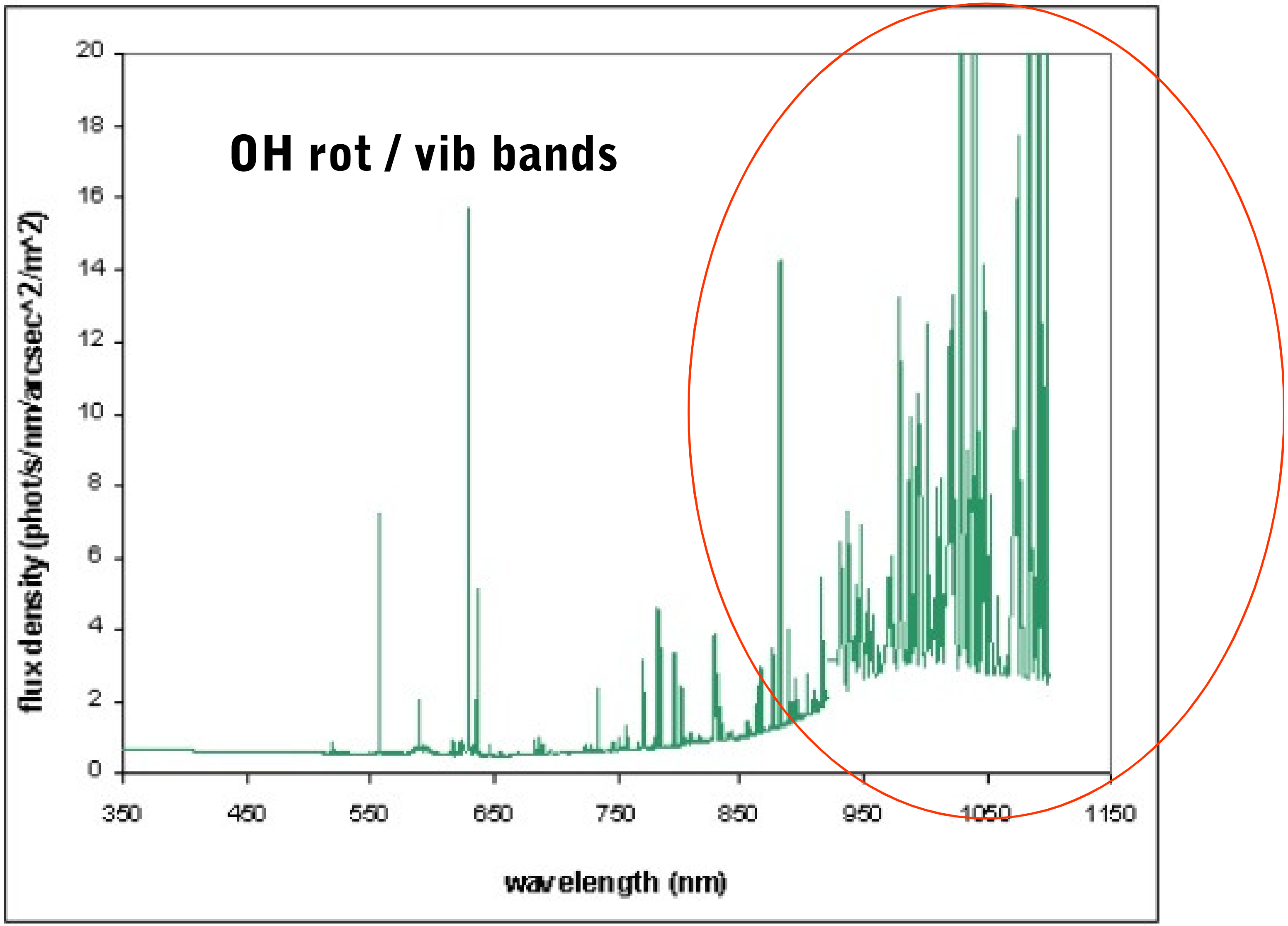
SKY BRIGHTNESS SETS A LIMIT ON WHAT WE CAN DETECT

Sky Brightness during the various lunar phases

	Sky Brightness (mag/arcsec2)				
lunar age (days)	U	B	V	R	I
0	22.0	22.7	21.8	20.9	19.9
3	21.5	22.4	21.7	20.8	19.9
7	19.9	21.6	21.4	20.6	19.7
10	18.5	20.7	20.7	20.3	19.5
14	17.0	19.5	20.0	19.9	19.2

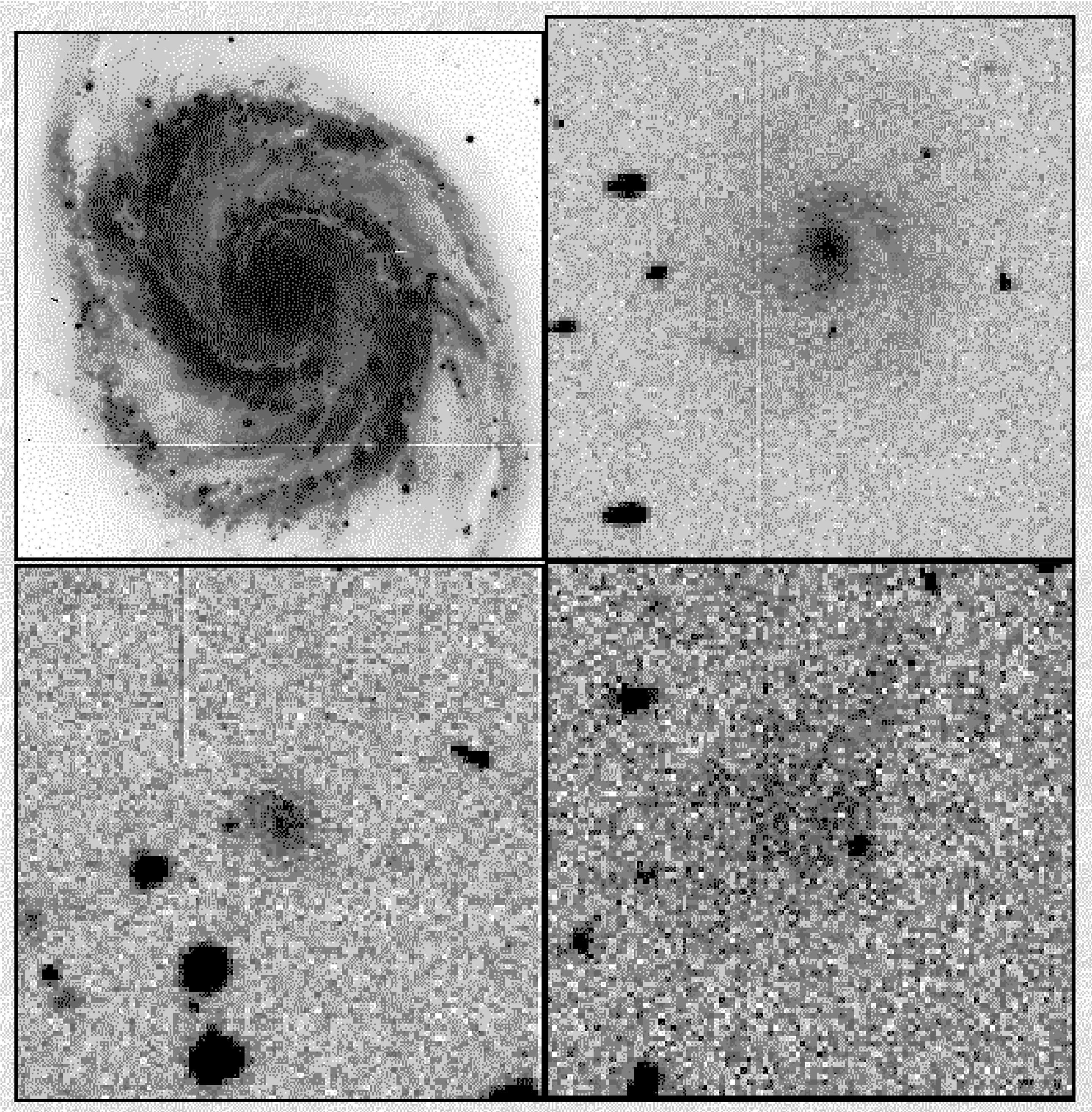
SKY BRIGHTNESS SETS A LIMIT ON WHAT WE CAN DETECT

AIR-GLOW



The sky spectrum at optical wavelengths from Mauna Kea. The night sky background is high at red wavelengths compared to blue. Hence one can reach fainter surface brightness levels when imaging at shorter wavelengths.

Zodiacal light : faint, whitish, triangular glow that appears to extend up from the area of the Sun along the zodiac(ecliptic). Accounts for 60% of the total skylight on a moonless night.

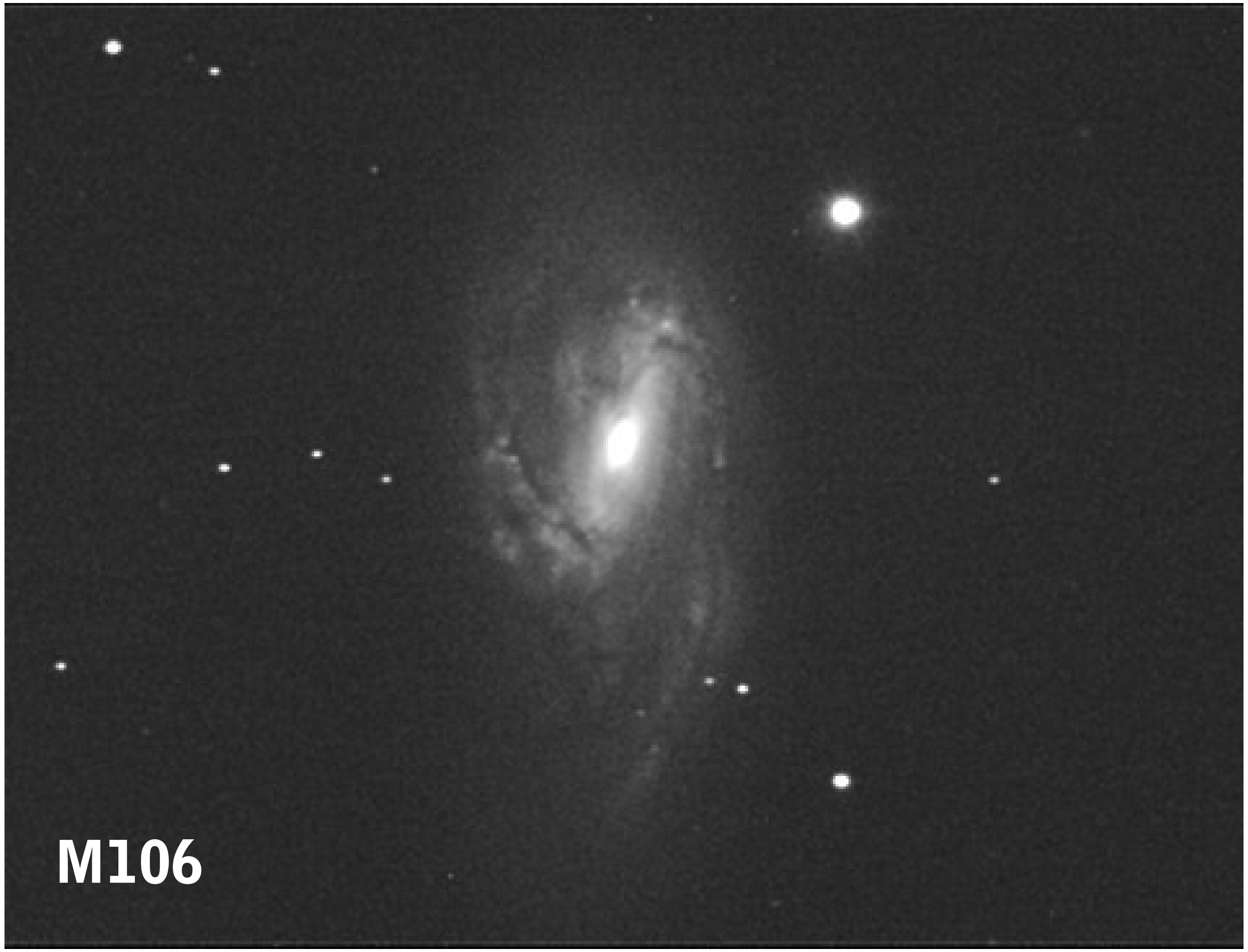


High surface brightness galaxy (upper left) compared with three low surface brightness galaxies.

Low surface brightness galaxies, which have low contrast compared to the brightness of the sky, are hard to find, even in the nearby universe.

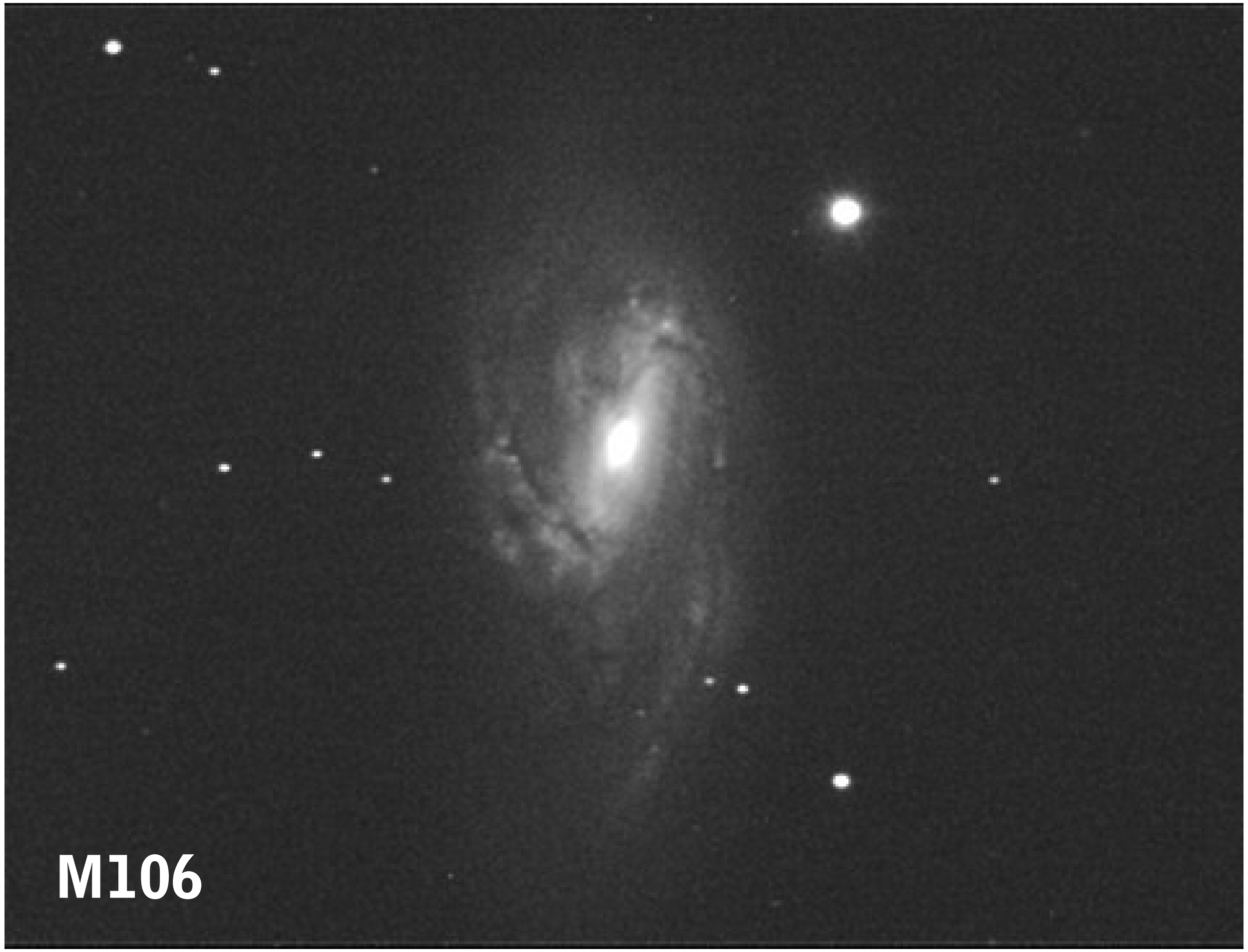
DEFINING THE SIZE OF A GALAXY

- **Galaxies do not have sharp edges**



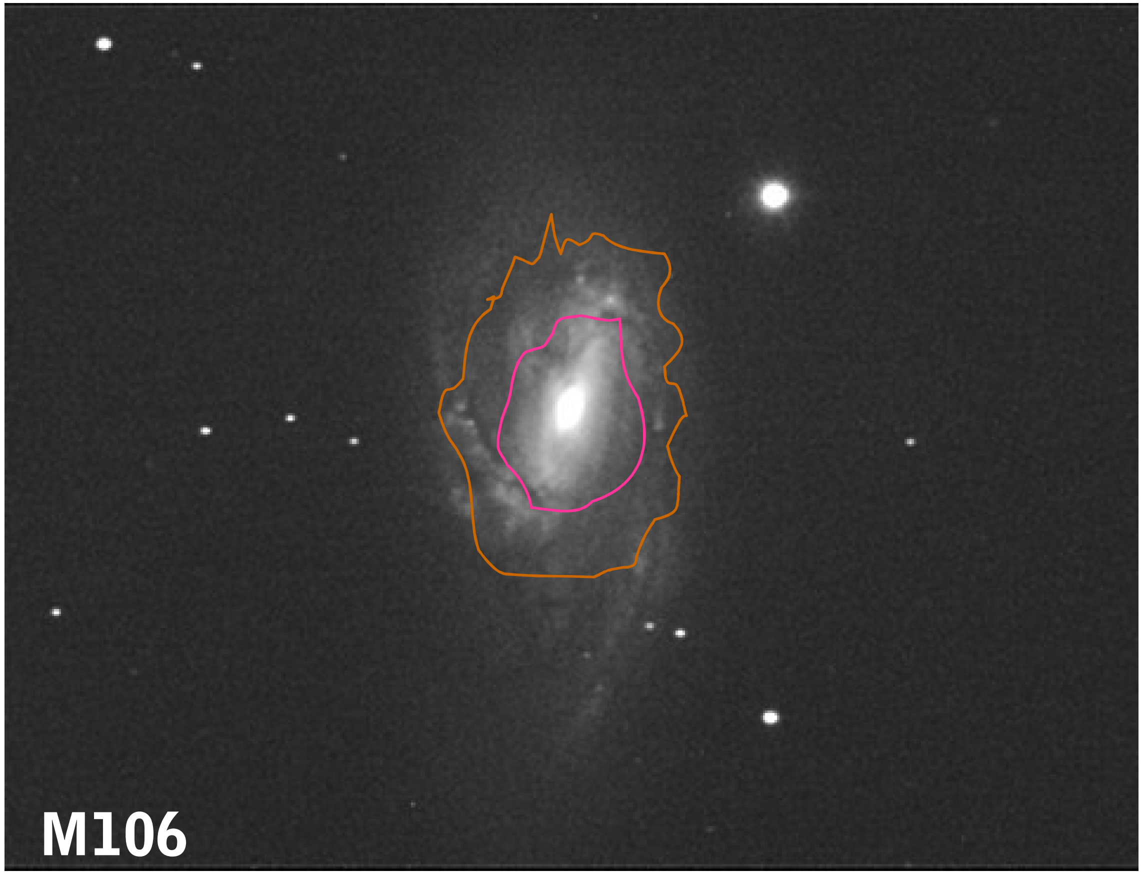
DEFINING THE SIZE OF A GALAXY

- **Size of a galaxy is specified by specifying the boundary with a certain surface brightness.**

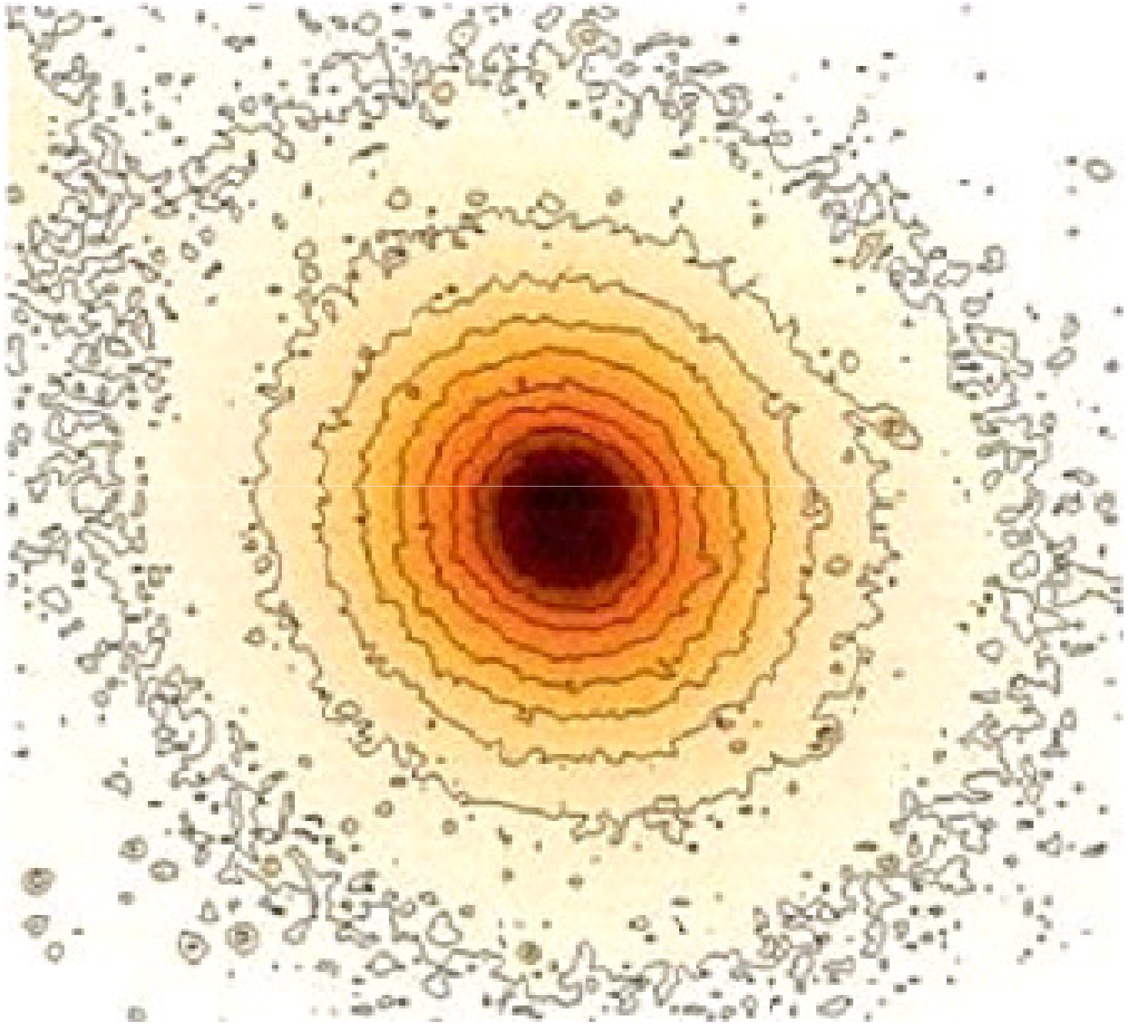


DEFINING THE SIZE OF A GALAXY

- **Contours of constant surface brightness are called isophotes, which is a closed curve connecting points of the same surface brightness.**



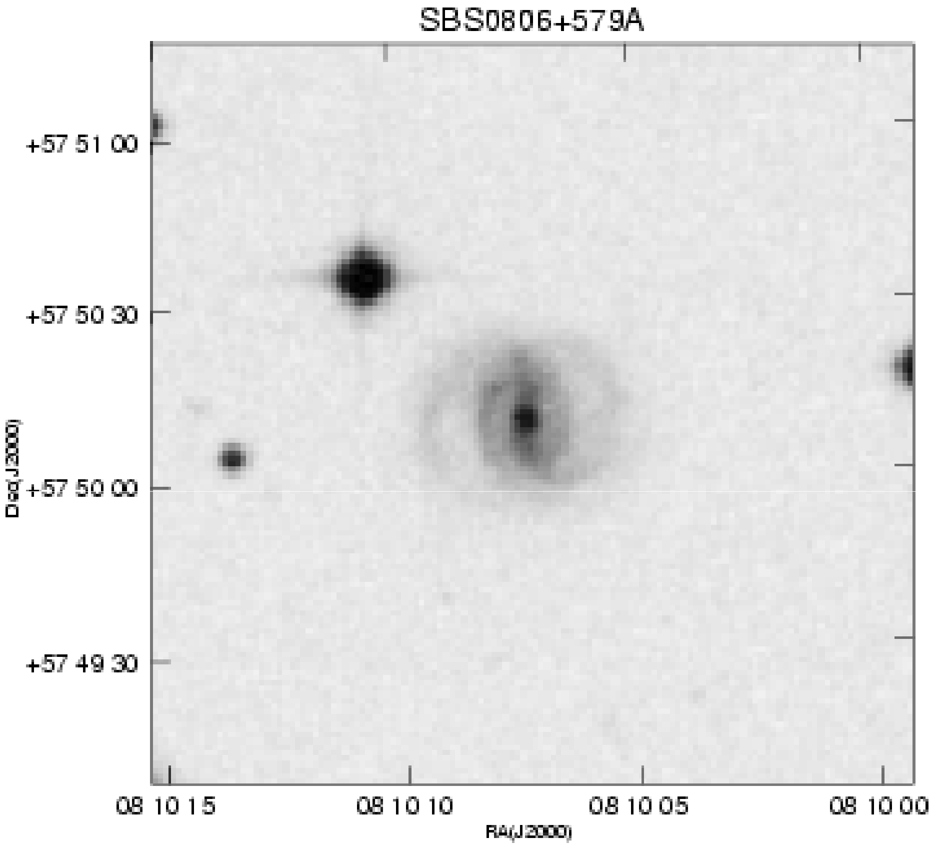
DEFINING THE SIZE OF A GALAXY

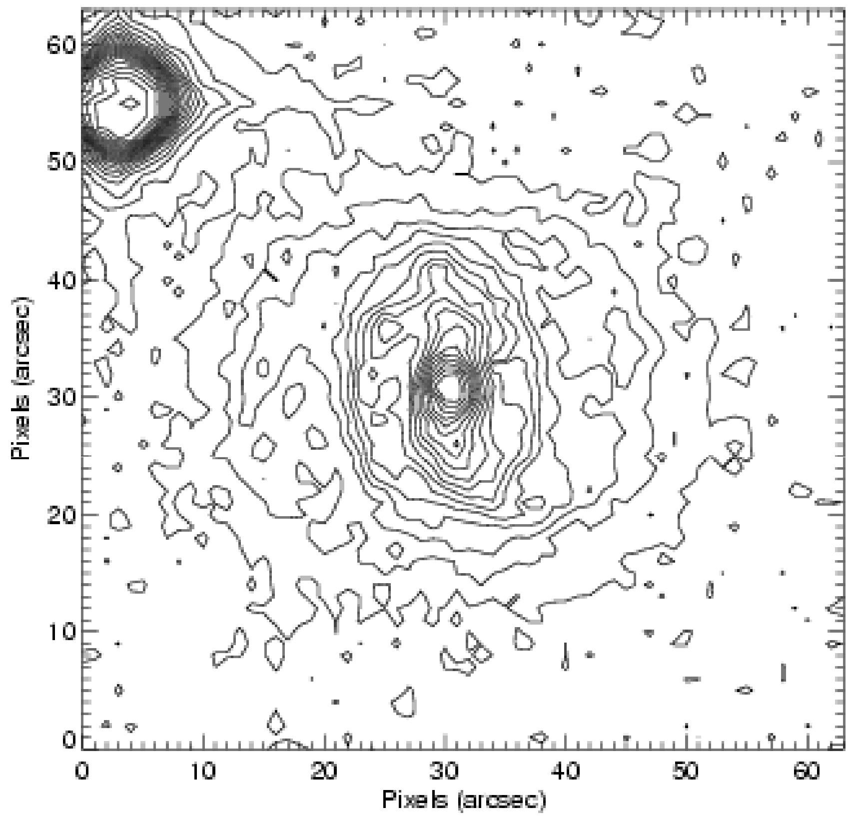


An elliptical galaxy with several isophotes drawn.

There is no isophotal contour that marks the edge of the galaxy. The outermost isophote does not mark the physical boundary of the galaxy.

DEFINING THE SIZE OF A GALAXY





Isophotal contours for a spiral galaxy

Huchtmeier et al. 2008

DEFINING THE SIZE OF A GALAXY

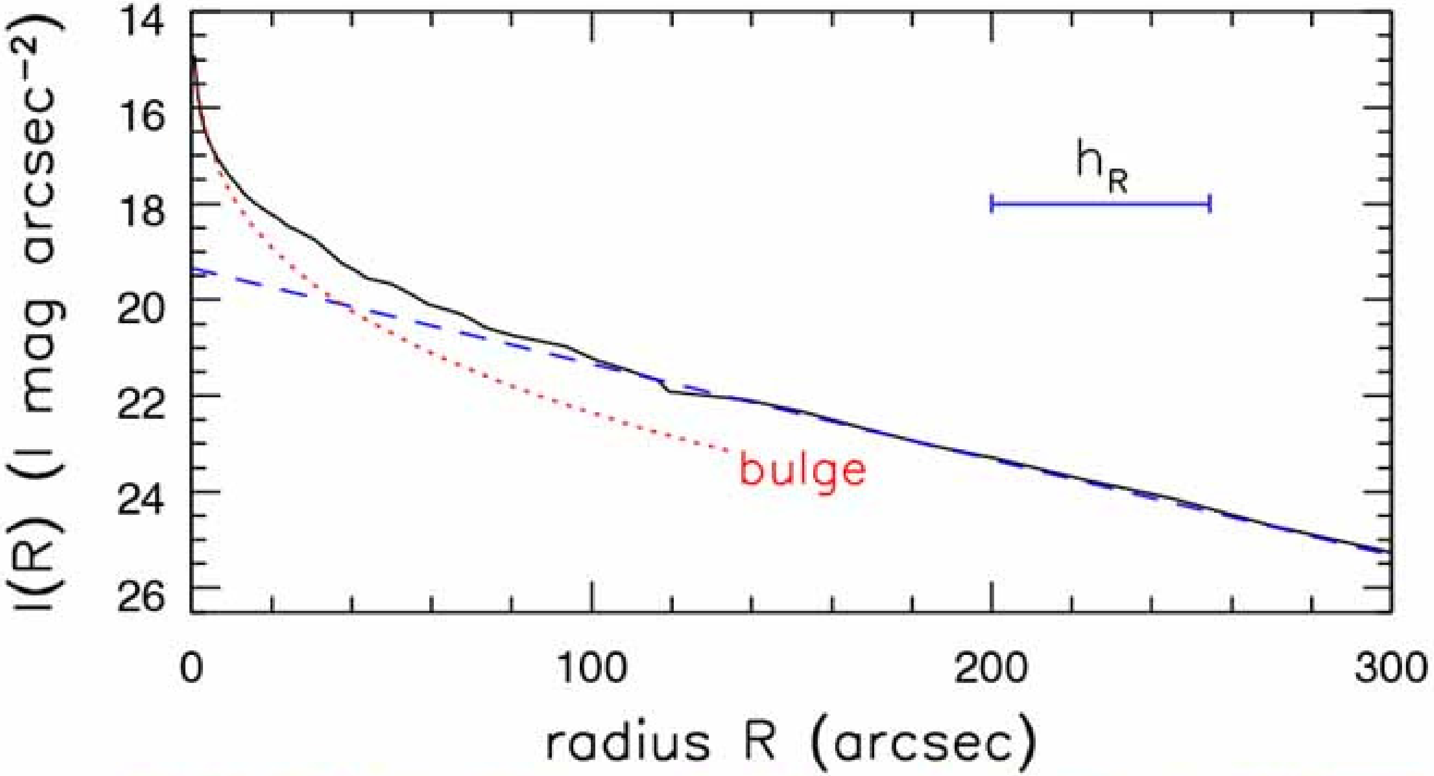


Fig 5.4 (R. Peletier) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

By measuring the apparent surface brightness of a galaxy over its brighter parts, it is possible to calculate its total flux by assuming that the surface brightness over its unmeasured regions follows a standard surface brightness profile.

Spiral galaxies : surface brightness - exponential fall off for disk + $r^{1/4}$ fall for bulge

Elliptical galaxies : surface brightness - $r^{1/4}$ fall-of